European Commission

NanoData Landscape Compilation

Photonics

Written by the Joint Institute for Innovation Policy, Brussels, Belgium, in co-operation with CWTS, University of Leiden, Leiden, Netherlands; Frost & Sullivan Limited, London, United Kingdom; Joanneum Research Forschungsgesellschaft mbH, Graz, Austria; the Nanotechnology Industries Association, Brussels, Belgium; Oakdene Hollins Limited, Aylesbury, United Kingdom; Tecnalia Research and Innovation, Bilbao, Spain; and TNO, The Hague, Netherlands

December 2015

Research and Innovation

EUROPEAN COMMISSION

Directorate-General for Research and Innovation
Directorate Industrial Technologies
Unit D.3 - Advanced Materials and Nanotechnologies

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European Commission
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EUROPEAN COMMISSION

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Directorate-General for Research and Innovation
2017 Key Enabling Technologies EN

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Luxembourg: Publications Office of the European Union, 2017.

PDF	ISBN 978-92-79-68385-5	doi: 10.2777/51249	KI-01-17-407-EN-N

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ACKNOWLEDGEMENT

The authors of this report wish to acknowledge the valuable guidance and support received from the numerous experts from research, industry and policy who were consulted during the project, through interviews, in workshops and other meetings, and via surveys and questionnaires.

EXECUTIVE SUMMARY

Background

Photonics emerged in the 1960s and 1970s from work on semiconductor light emitters, lasers and optical fibres. Nanoscale effects impact on photonics, e.g. in the surface quality of waveguides and optical fibres. The focus here remains as closely as possible on photonics as it relates to nanotechnology, e.g. where nanotechnology enhances photonics and *vice versa*. Photonics more widely is also described and referenced.

Role of nanotechnology

The main applications of photonics are in scanning, sensing and imaging systems; data transmission, storage, communication and networks; screens and displays; advanced lighting; photonic energy systems; and laser systems. Nanotechnology can be used to enhance the effectiveness of these, e.g. using nano-coatings. In addition, photonics is being applied at the nanoscale, e.g. in light-focussing in photovoltaics, in sensors and in lasers. Amongst the applications are:

- In health: in lasers (for eye surgery, commonly needed by older people), in sensors (for medical diagnosis and systems for independent living) and in point-of-care diagnostics;
- In food safety and security: in scanning technologies (for barcodes, production line quality assurance) and systems for the efficient use of resources such as water and fertilisers;
- In manufacturing processes: to prevent waste of natural resources; and
- In energy: to reduce consumption through more efficient and novel lighting systems (e.g. smart lighting, OLEDs) and increased clean production from photovoltaics.

Photonics is used in manufacturing at the nanoscale (e.g. integrated circuits) and in materials processing (e.g. laser cutting). It is also an enabler for measurement at the nanoscale, e.g. to examine the structure of (living) cells.

Policies

Photonics is highly multi-disciplinary and can be applied as an enabler in multiple sectors: food and drink, transport, media and communications, defence, manufacturing and production, construction, healthcare, the environment and ICT. Photonics and nanotechnology are therefore impacted upon and supported by many policies and programmes. Within the Framework Programmes, photonics mainly falls under ICT. There are several significant initiatives in the European context, amongst them the European Technology Platform Photonics21; the ERA-NET ERASPOT (Strengthening Photonics and Optical Technologies for Europe); the ERANET-Plus actions under FP7: PIANO+, OLAE+ and BiophotonicsPlus; the Network of Excellence PHOTONICS4LIFE; and the EU contractual Public Private Partnership (cPPP) on photonics.

National Member State (MS) policies and programmes to support photonics and nanotechnology include the Austrian NanoInitiative, the Dutch NanoNextNL, Spain's Strategic Action for Nanoscience and Nanotechnology, New Materials and New Industrial Processes (SANSNT), France's Agence National de la Recherche and its programme on Nanotechnologies and Manufacturing, and Germany's programmes on Optical Technologies and on Photonics Research.

Other countries have policies and programmes for nanotechnology, some of which specifically fund photonics and nanotechnology activities by agencies or research bodies, e.g. under the National Nanotechnology Initiative in the US (under the National Science Foundation and the Department of Energy); under the megaproject label in China; in Korea at KIST; and under A*STAR in Singapore (at its Institute of Microelectronics).

Other EU and MS policies focus on the need for scrutiny of the use of nanotechnologies including developing strategies to test the safety of engineered nanomaterials. The European Standardisation Committee (CEN) has a dedicated technical committee for nanotechnologies, addressing health, safety and environmental aspects. Nanotechnology in photonics was seen as relatively low risk for consumers and workers alike.

EU R&D projects

For projects at the European level, nanosciences and nanotechnologies (NT) were first provided for at a significant level in FP6, taking about 10% of the budget (EUR 1,703 million for nanotechnology out of EUR 16,692 million for FP6) mainly under the headings of NMP (EUR 870 million), Information

Society (EUR 346 million) and Life Sciences (EUR 54 million), as well as Human Resources and Mobility (Marie Curie Actions, EUR 219 million).

The 483 projects associated with research and innovation activities in nanotechnology and photonics received funding of EUR 737 million, equivalent to 11.6% of the funding for nanotechnology and 1.2% of the overall FP budget. The type of participants receiving most EC funding are higher education organisations with 55.2% of the total funding for nanotechnology photonics activities followed by research organisations with 31% of funding. SMEs and large companies take 7% and 6% respectively.

In FP7, the largest proportion of activities specific to nanotechnology and photonics took place under Co-operation, with 79 projects and EUR 270 million (48.3% of funding). ICT had the largest number of nanotechnology photonics projects (46) and a total of EUR 131 million of EC funding (23% of the total for nanotechnology photonics). NMP (Nanosciences, nanotechnologies, Materials and new Production technologies) had 26 projects, EUR 111 million of funding (20% of nanotechnology photonics FP7 funding). Under the strand called Ideas, the European Research Council activities had 31% of the funding (EUR 173 million) and 102 projects. Marie Curie Actions (People) are responsible for most of the remaining funding with 18.5% of the nanotechnology photonics total (EUR 104 million) and 198 projects.

Throughout FP6 and FP7, Germany, France, the United Kingdom, Spain and Switzerland are the top participant countries, more active in nanotechnology photonics than in nanotechnology or FP overall. The Netherlands is less active in nanotechnology photonics than in nanotechnology or FP overall, as is Belgium. This may reflect the emphasis in those countries on the more industrial end of the research and development scale, with the Dutch NanoNextNL and the Belgian IMEC[1] centre.

In terms of individual organisations in the EU28, CNRS and CEA lead the way for France with the highest shares of FP funding followed by the Italian Consiglio Nazionale delle Ricerche. Imperial College (UK) is the highest placed higher education institute, followed by the University of Cambridge.

Company participation is rather modest in nanotechnology photonics research. The company receiving the most funding was only in 27th position in the overall list of nanotechnology photonics FP participants. It was S.O.I. Tec Silicon on Insulator Technologies SA (FR), the co-ordinator for the JTI project AGATE-Development of Advanced GaN Technologies. IBM Research GmbH (CH) is in second place among the companies but in 48th position in nanotechnology photonics FP overall. These first two companies are followed by Aixtron SE (DE), Philips Electronics Nederland (NL) and Thales SA (FR).

Publications

Publication data shows a global output for nanotechnology and photonics together of c. 86,000 publications in 2000-2014. Over 28,000 publications were produced in EU28&EFTA countries (includes Switzerland and Norway), 33% of the total World NP publications in the time period. The share of EU28&EFTA has however gradually decreased over time from almost 44% to 28% most likely due to the rise in publications in China and other developing and emerging economies. The strongest publishing region for nanotechnology and photonics in 2014 was Asia, followed by EU28 & EFTA and North America. The most prolific country was China (PRC), followed by the US, Germany, India and Japan. In the EU28&EFTA, Germany generated the largest number of publications in 2012, followed by the United Kingdom, France and Italy.

The higher education organisations with the most nanotechnology/photonics publications globally in 2014 were predominantly Asian universities, followed by those of the US and UK. The EU28 & EFTA higher education organisations with the most NP publications globally in 2014 were the University of Cambridge (UK), Imperial College London (UK) and the Technical University of Denmark (DK). There has been, however, no normalisation of the data to take into account factors influencing publication output, such as the number of researchers/technicians/students or the research budgets. Publishing at a much lower level also takes place in companies - in 2014 the leaders for publications were IBM, NTT, Samsung and Philips.

[1] Interuniversitair Micro-Elekctronica Centrum Vzw

Patenting

Between 1992 and 2011, the number of photonics patent families identified among the nanotechnology patents was 1,693, 3.8% of all nanotechnology patent families. The prevalence of countries such as Germany, the United Kingdom and France continues as patenting patterns in the EU28 are reviewed (although patenting is greatly dominated by the US and its research-performing organisations. The Netherlands, Spain and Italy, Denmark and Sweden all feature also but at some distance. In Asia, the lead country for applicants, Japan (398), is followed by Korea (95), Taiwan[2] (46), China (30) and India (9).

Using patenting families[3] as the measure, the top EU28 countries for nanotechnology photonics patenting between 1993 and 2011, both by filing country and by country of applicant, were the United Kingdom, Germany and France. The top EU28 countries for patent filings[4] and for granted patents were the same and were led by Germany, France and the United Kingdom.

Of the top ten universities and public research organisations (PROs) with the highest number of patent families (with percentages for PCT, US and EP applications), just one is in the EU28 (CNRS, France) and six are in the US. Japan (2) and Korea make up the remainder. Amongst EU28 and EFTA countries, French organisations perform strongly (three of the top ten), as do German organisations (three of the top ten but with lower patent numbers).

Company patent applications are dominated by Japan. In the top ten companies for patent applications in EU28 and EFTA countries, four are from Germany, three from the UK and one each from the Netherlands, France and Denmark. In terms of patents granted, Japan is also strong with four companies in the top ten for EPO patents granted and seven of the top ten for USPTO patents granted. Companies from Germany (Deutsche Telekom) and France (Thales) each have one EPO patent.

Products and markets

Over 150 photonics-related products using nanotechnology have been identified as being commercially available. The majority fall into the application areas of advanced lighting, screens and displays, and other optical applications, as well as electronics for the scanning, sensing and imaging systems and for data transmission, storage and communication. Nanotechnology is particularly important in photonics in photovoltaics (PV or solar cells), light emitting diodes (LEDs), organic light emitting diodes (OLEDs) and near field optics. Over 20% of the products identified are optical and anti-scratch/ anti-stick coatings, the largest share, while nano-lithography accounts for the second largest share amongst commercially-available products with 15%. Further shares worth mentioning are microscopes (11%) and flat panel displays (10%).

The products can be divided into nano-coatings and thin films (for lenses, optical fibre cladding, etc.); thin films (for optical recording media and light-emitting diodes LEDs, etc.); nanotools (such as microscopes and lithographic tools); emerging areas (using quantum dots, carbon nanotubes and graphene); and long-term prospects (based on electron spin, such as spintronics).

Global sales for nanotechnology products in the photonics sector were estimated to be USD 7.9 billion in 2013 and are forecast to be over USD 29 billion in 2019, a compound annual growth rate (CAGR) of over 24%. Most of the growth is expected to come from existing commercialised products, making up over 80% of the expected market value in 2019, the remainder being from emerging products (USD 5.5 billion in 2019). [5]

Regulation and standards

European regulations for nanotechnology are well-advanced with definitions and many regulatory documents but nanotechnology photonics are not regulated *per se* being characterised by the wavelength of the emitted light being in the nanoscale rather than by the materials used. Nanomaterials used for the realisation of photonic devices are nevertheless regulated under REACH

[2] Chinese Taipei
[3] At the European Patent Office, US Patent and Trademark Office or World Intellectual Property Office
[4] Measured by number of patent families
[5] BCC Research

in the EU and national regulations. Regulations for electronics, such as the Waste Electrical and Electronic Equipment Directive (WEEE) and the Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment, may also apply.

The standardisation of photonics is shared amongst several technical committees (TC) of the International Standardisation Organisation. The dedicated ISO/TC for photonics is ISO/TC 172 Optics and photonics. Nanoscale aspects of photonics are covered by ISO/TC 229 Nanotechnologies and IEC/TC 113. A technical specification ISO/DTS 80004-10 Nanotechnologies -- Vocabulary -- Part 10: Nano-enabled photonic components and systems is currently under development. Other electronic aspects are covered by IEC/TC 76 Optical radiation safety and laser equipment.

In Europe, the European Standardisation Committee (CEN) has a dedicated technical committee TC 352 that has been working with nanotechnologies. CEN/TC 123 Lasers and photonics and CEN/TC 352 Nanotechnology are responsible for the same issues as mentioned above for ISO. They have, however, not developed standards relevant to nanotechnology and photonics.

Further analysis of the environment for nanotechnology photonics and the effects of European policies and actions on nanotechnology photonics will be reported in the NanoData Photonics Impact Assessment.

1 BACKGROUND

> *'Photonics is the science of the harnessing of light. Photonics encompasses the generation of light, the detection of light, the management of light through guidance, manipulation, and amplification, and, most importantly, its utilisation for the benefit of mankind.'*
>
> Pierre Aigrain (1967)

This report is concerned with the application of nanotechnology to photonics. The term photonics describes the generation, emission, transmission, modulation, signal processing, switching, amplification, detection and sensing of light particles (photons).

This report examines the use of nanotechnology for photonics from the perspectives of:

- The knowledge base (projects, publications, patents and the organisations involved);
- The economic importance of nanotechnology (the products and markets); and
- Regulation and standards, environmental health and safety (EHS).

Given the wide use of photonics throughout manufacturing and the range of sectors on which it impacts, there will be some overlap with other sectors considered within the project, for example, health, energy and ICT (information and communications technologies).

Unless otherwise stated in the text, the data has been extracted[6] from the NanoData project database compiled from a range of statistical sources (e.g. European Commission, publication databases, patent office databases, etc.) and primary research via literature review and other data collection methods (e.g. interviews).

The abbreviation PH is sometimes used in the report for photonics through nanotechnology. Nanotechnology and photonics, or nanotechnology photonics, may also be abbreviated to nano-photonics in certain cases.

[6] The data was originally obtained from various sources (e.g. patent and publication databases) using keywords. The keywords for each sector were identified via literature searches and discussions with experts such that there would be a unique set of keywords for each sector. The intention was that all the data identified would be relevant to the sector. However, some data may be missing as the keywords have been limited to those relevant to photonics and not to other sectors. Where confusion or error could have resulted, the keyword has been omitted.

2 INTRODUCTION TO PHOTONICS AND NANOTECHNOLOGY

2.1 Overview

The discipline of photonics emerged from work on the first practical semiconductor light emitters (invented in the early 1960s) and lasers and optical fibres (developed in the 1970s). In principle, photonics covers wavelengths, from gamma rays to radio waves, including X-ray, ultraviolet, visible and infrared light.

2.2 Photonics and its applications

The main uses of (nano)photonics are[7]:

- Scanning, sensing and imaging systems;
- Data transmission, storage, communication and networks;
- Screens and displays;
- Advanced lighting;
- Photonic energy systems; and
- Laser systems.

Photonics is in everyday usage. In telecommunications, it enables information (in the form of light pulses) to be transmitted along optical fibres, with thousands of times more information being carried in this way than can be achieved using electrical wires. Photonic devices are used to convert electrical signals to and from optical signals at the interface with the optical fibres. Data can be transmitted through complex systems at the speed of light with low losses. Photonics is also used in sensors (e.g. barcode scanners); in health (e.g. for eye surgery); in defence and security (e.g. infrared cameras, remote sensing); in energy applications (e.g. photovoltaics); in consumer products (such as laptops and smart phones); and in light detectors and waveguides (in the form of quantum dot materials).

Photonics is used in manufacturing at the nanoscale (e.g. integrated circuits) and in materials processing (e.g. laser cutting). It is an enabler for measurement[8] at the nanoscale, e.g. in examining cellular structures via super-resolution imaging systems operating below 50nm and even as low as 20nm optical resolution. Signalling pathways for immune diseases, neurological disorders and cancers are increasingly being mapped using such commercialised, albeit still expensive, research tools.

2.3 The role of nanotechnology in photonics

Photonics plays a role in addressing many of the societal challenges faced globally today.

"Ageing is one of the greatest social and economic challenges of the 21st century for European societies. It will affect all EU countries and most policy areas. By 2025 more than 20% of Europeans will be 65 or over, with a particularly rapid increase in numbers of over-80s."[9]

Healthy ageing is just one of the many societal challenges for which photonics offers solutions. Photonics is used in lasers (for eye surgery, commonly needed by older people), in sensors (for medical diagnosis and systems for independent living) and in point-of-care diagnostics.

Healthy ageing: Cancer diagnosis and treatment and photonics

Cancer is one of the biggest challenges associated with the ageing society. Photonic technologies are already applied relatively widely in laboratory testing for diagnosis, but their use for in-vivo diagnosis and treatment is limited to photodynamic therapy and to fluorescence endoscopy for detecting tumour lesions during surgery.

[7] "The Leverage Effects of Photonics Technologies: the European Perspective", A Study for EC DG Information Society and Media under SMART 2009/006 (2011)
[8] NEA Foresight Report, The Nanophotonics Industry Association, 2011.
[9] http://ec.europa.eu/health/ageing/policy/index_en.htm

This is likely to change within the next few years since photonic technologies offer clear advantages over established technologies such as X-ray and ultrasound: they have better resolution, are more specific and can produce results in real time. New markets will emerge from innovative photonic technologies, especially by the combination of existing photonic and non-photonic imaging methods such as positron emission tomography (PET). The world market for optical technologies in healthcare is EUR 23 billion, and this is growing at 8% CAGR that will yield a market approaching EUR 43 billion by 2015. The market for biophotonics is even larger at EUR 70 billion.

Source: Taken from http://ec.europa.eu/enterprise/sectors/ict/files/kets/photonics_final_en.pdf

Photonics contributes to food safety and security with scanning technologies (for barcodes, production line quality assurance) and to systems for the efficient use of resources such as water and fertilisers. Likewise, photonics can reduce wastage of natural resources in manufacturing processes.

In the energy domain, photonics offers lower energy consumption through more efficient and novel lighting systems (e.g. smart lighting, OLEDs) and cleaner production via photovoltaics, as well as potentially addressing the challenge of insufficient seasonal daylight in some regions of the world.

Grand Societal Challenges for Europe

The European Union has identified the following grand societal challenges to be addressed, inter alia, by the Framework Programmes for Research and Innovation:

- Health, demographic change and wellbeing;
- Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the bio-economy;
- Secure, clean and efficient energy;
- Smart, green and integrated transport;
- Climate action, environment, resource efficiency and raw materials;
- Europe in a changing world - inclusive, innovative and reflective societies; and
- Secure societies - protecting freedom and security of Europe and its citizens.

Photonics supports the security and freedom of Europe through defence applications (e.g. robotics and infra-red sensing), and video surveillance and biometric sensing at borders (for detection of unauthorised goods and people). Each of the seven European Grand Societal Challenges (see box above) is being addressed using photonics.

The next section looks at the policies at European Union and Member State levels that are supporting the development of nanotechnology and photonics.

3 EU POLICIES AND PROGRAMMES FOR NANOTECHNOLOGY AND PHOTONICS

Given that photonics has a role in enabling sectors as diverse as:

- Food and beverages (e.g. use of photonics for sensing scanners on production lines);
- Vehicles and large machinery (e.g. in vehicle production and automotive lighting);
- Advertising and visual media (e.g. in flat screen displays and projection equipment);
- Defence and security systems (e.g. in infrared imaging systems);
- General manufacturing (e.g. welding and measuring);
- Production lines (e.g. imaging for robotics);
- Healthcare and medicines (e.g. laser eye surgery);
- Construction (e.g. in sensors for buildings);
- Environmental monitoring (e.g. thermal infrared remote sensing for water management);
- Transportation (e.g. automatic tolling and congestion charging); and
- Telecommunications (e.g. DVD players and smart phones).

and that there is a very high level of multi-disciplinarity required in its research and development, the policies that affect it are many and varied. Within the European Framework Programmes, specifically the Seventh Framework Programme (FP7), it falls under the heading of information and communications technologies (ICT).

3.1 The EU Framework Programmes: supports for nanotechnology

Scenario work in the 2011 report for the European Commission[10] identified the strengths and weaknesses of photonics in Europe, seeing the future as uncertain and highly dependent on future policy decisions. While the industry was perceived to be quite robust in Europe, its rate of growth was expected to be dependent on meeting rapidly changing market demands. This flexibility was seen as possible to achieve, given the large number of SMEs active in photonics in Europe.

Of greater concern was the low volume production in Europe, particularly as high-growth areas were predicted to be in consumer goods, not a strong European market. In this scenario, the strong link between research and industry in photonics in Europe was seen as being less of an advantage, and it brought to the fore the need for initiatives more widely across the value chain to support SMEs and indigenous higher-volume manufacturers. Alternatively, Europe could focus on high-end, high-value products only and leave high-volume production to Asia, resulting in a strong import market for photonics-related consumables. Thus, greater attention to SMEs and research-active industry would be one possible focus, the other being a focus on support for high-volume manufacturing. The main messages from the scenario analysis in the report are given in the box below.

"The Leverage Effects of Photonics Technologies: the European Perspective"

Main messages from the scenario analysis:

- The European photonics research and industry at large is robust against future developments, because of its highly innovative nature and strong position in manufacturing;
- Lack of volume production can jeopardise the linkage of certain parts of European research to industry, weakening the latter's position;
- Focus of the European research and industry in general should be on high performance, low volume, highly innovative markets (although in some markets, the European industry is a major player in high volume markets);
- The relationship between governments, research and industry is a crucial factor to competitiveness. Especially public support for research and innovation increases the competitive advantage, including the opportunity for more radical innovations;

[10] "The Leverage Effects of Photonics Technologies: the European Perspective", A Study for EC DG Information Society and Media under SMART 2009/006 (2011), lead consultant TNO.

- Focus on reduction of energy consumption, or greening of photonics not only is crucial for environmental sustainability, but also to the economic sustainability; and
- Support of SMEs, especially to enhance their participation in supply chains will further enhance the competitiveness of the photonics research and industry due to their capacity to adjust to new opportunities.

Source: "The Leverage Effects of Photonics Technologies: the European Perspective", A Study for EC DG Information Society and Media under SMART 2009/006 (2011)

The actions being taken to support for public sector research and development (R&D) in the European Union are funded by Member States either directly through national programmes or indirectly via the programmes administered by the European Commission and its agencies. In addition, research and development are funded by companies (intra- and extra-mural R&D) and by philanthropic bodies and individuals. This report concentrates mainly on funding via the European Commission (EU funding), Member State funding and the outputs of industry funding of its own R&D.

The Framework Programmes being the largest source of EU funds for R&D, they have the greatest role in EU funding of nanotechnology R&D. Support specifically named as being for nanosciences and nanotechnologies was first provided at a significant level in the Sixth Framework Programme (FP6, 2002-2006)[11]. Nanotechnology funding in FP6 was followed up with targeted funding in the Seventh Framework Programme (FP7, 2007-2013), the largest part specific to nanotechnology being the "Nanosciences, Nanotechnologies, Materials and new Production Technologies (NMP)" theme under the Co-operation Programme. Once again, this specific activity for nanotechnology has played the most significant role in supporting nanotechnology research. EUR 3.5 billion have been allocated for NMP over the duration of FP7 with the emphasis on:

- Nanosciences and nanotechnologies - studying phenomena and manipulation of matter at the nanoscale and developing nanotechnologies leading to the manufacturing of new products and services;
- Materials - using the knowledge of nanotechnologies and biotechnologies for new products and processes;
- New production - creating conditions for continuous innovation and for developing generic production 'assets' (technologies, organisation and production facilities as well as human resources), while meeting safety and environmental requirements; and
- Integration of technologies for industrial applications - focusing on new technologies, materials and applications to address the needs identified by the different European Technology Platforms (see also below).

The main part of FP7 that is relevant to photonics is ICT. ICT Challenge 3 (Alternative Paths to Components and Systems) covers nanoelectronics and photonics and the integration of these technologies with related components and systems, as well as advanced computing and control systems at a higher level. It also addresses energy, resource and cost efficiency including recycling and end-of-life issues. The Challenge aims to:

- Reinforce European industrial leadership in nano-electronics and photonics as key enabling technologies;
- Enable further integration and cross-fertilisation of key enabling technologies towards building energy- and resource-efficient components and systems;
- Expand Europe's industrial leadership in embedded and mobile computing systems; and
- Promote inter-disciplinary research and innovation activities by bringing together different research domains and constituencies.

[11] FP6 NMP: Nanotechnologies and nanosciences, knowledge-based multifunctional materials and new production processes and devices: thematic priority 3 under the 'Focusing and integrating community research' of the 'Integrating and strengthening the European Research Area' specific programme, 2002-2006.

FP7-ICT Example: Access CenTre for PHotonics innovAtion Solutions and Technology support (ACTPHAST)

ACTPHAST (Access CenTre for PHotonics innovAtion Solutions and Technology support) is a "one stop shop" European access centre for photonics innovation solutions and technology support. ACTPHAST aims to support and accelerate the innovation capacity of European SMEs by providing them with direct access to the expertise and state of the art facilities of Europe's leading photonics research centres, enabling companies to exploit the commercial potential of applied photonics. Technologies available within the consortium range from fibre optics and micro-optics, to highly integrated photonic platforms. Capabilities cover the range from design through to full system prototyping. ACTPHAST is geographically spread to ensure that all of Europe's SMEs can avail of timely, cost effective, and investment free photonics innovation support, and that the extensive range of capabilities within the consortium can impact across a wide range of industrial sectors, from communications to consumer related products, biotechnology to medical devices.

Co-ordinated by VUB in Belgium, ACTPHAST has 28 partner organisations in eleven Member States.

See: www.actphast.eu
See also: ACTMOST at http://www.actmost.eu/

Nanotechnology photonics is funded under other programmes within EU funding but the Framework Programme remains the largest designated source of R&D budget. Within FP7, in addition to the Co-operation Programme, non-specific basic research, People and Capacities are funded and each of these provides potential funding for nanoscience and technology including nanotechnology and photonics. Significant examples of these are:

- The European Research Council funding of up to EUR 7.5 billion in FP7 (and EUR 13.1 billion in 2014-2020 under Horizon 2020[12]) for investigator-driven, bottom-up research ideas in science, engineering and interdisciplinary research, awarded through open competition;
- The Marie Curie Actions[13], with funding of up to EUR 4.7 billion FP7 in 2007-2013 (and EUR 6.16 billion Horizon 2020 funding in 2014-2020) for training, mobility and career development of researchers; and
- The Capacities Programme[14], with a budget of EUR 4.1 billion, funding for research infrastructures; for research for the benefit of SMEs; for regions of knowledge and support for regional research-driven clusters; for research potential of Convergence Regions; for science in society; for support to the coherent development of research policies; and for international co-operation.

Within the Framework Programmes are specific schemes including ERA-NETs and Networks of Excellence as well as collaboration mechanisms on infrastructure.

The ERA-NET scheme began under FP6 to support collaboration between and co-ordination of national research programmes and included, for example, a network on nanotechnology and photonics: ERA-SPOT - Strengthen Photonics and Optical Technologies for Europe (2005-2009, total funding EUR 880,000). Initiated by funding agencies from Austria, France, Germany, Slovenia, and Sweden, ERA-SPOT aimed to consolidate research funding activities in Optical Technology (OT) throughout Europe via the co-ordination of national programmes, developing and implementing joint strategies and actions.

The ERA-NET scheme was continued under FP7 to develop and strengthen the co-ordination of national and regional research programmes through ERA-NET Plus (ERANET+) actions - providing,

[12] http://erc.europa.eu/
[13] http://ec.europa.eu/research/mariecurieactions/ Marie Curie Actions became Marie Skłodowska-Curie Actions under Horizon 2020.
[14] http://ec.europa.eu/research/fp7/index_en.cfm?pg=capacities

in a limited number of cases with high European added value, additional EU financial support to facilitate joint calls for proposals between national and/or regional programmes. Three ERANET+ actions targeting photonics were funded:

- PIANO+[15]: a trans-national call for project proposals on "photonics-based internet access networks of the future" was launched in March 2010. It was co-funded by national funding bodies from Austria, Germany, Israel, Poland and the United Kingdom and by the European Commission. The multi-national research projects funded under PIANO+ were implemented between 2011 and 2014.
- OLAE+[16] (2011-2016, funding EUR 6 million) Organic and Large Area Electronics European Competition for Collaborative R&D Funding: an initiative to consolidate funding activities on OLAE technology, materials, and systems throughout Europe, thereby achieving the best possible exploitation of the resources and innovative potential of European industry and science. The theme and basic concept for this ERANET+ originated from the Mirror Group of the European Technology Platform Photonics21 comprised of governmental representatives from the Member and Associated States involved with the promotion of photonics.
- BiophotonicsPlus[17] (2012-2013, funding EUR 15 million): a joint initiative of the regions of Catalonia (Spain), Flanders (Belgium) and Tuscany (Italy) as well as Germany, Israel, Latvia, and the United Kingdom. The aim was to stimulate and fund R&D projects which will translate existing biophotonic technology and methods into appliances and put them into clinical, medical or industrial practice. Government grants have been awarded to innovative projects involving participants from at least two of the participating countries or regions.

Networks of Excellence (NoE) were introduced in the Sixth Framework Programme (FP6) with the objective of combating fragmentation in the European Research Area by integrating the critical mass of resources and expertise needed to enhance Europe's global competitiveness in key areas relevant to a knowledge-based economy. These bottom-up initiatives are led by consortia targeting specific research or technological challenges. The Network of Excellence PHOTONICS4LIFE is focusing on bio-photonics for health and medical applications.

PHOTONICS4LIFE – A European Network of Excellence

The focus of the Network of Excellence PHOTONICS4LIFE is on bio-photonics, one driver of the trend towards personalised medicine, a tool for enhancing diagnosis, therapy and follow-up care. Its application is expected to contribute to addressing the accelerating challenges associated with population ageing and the consequent increase in age-related diseases, hereby helping to limit healthcare costs.

As a Network, PHOTONICS4LIFE aims to provide a coherent framework for the highly-fragmented field of bio-photonics in Europe. It is working to bridge the gap between disciplines ranging from physics and chemistry via engineering to biology and medicine, while also linking the expertise of research institutes with that of SMEs and large companies.

Thirteen core partner institutions from ten countries (Belgium, Finland, France, Germany, Italy, the Netherlands, the Russian Federation, Spain, Sweden and the United Kingdom) were the founder members of the Network in 2008. These were later joined by Associated Partners from those and six other countries (Denmark, Greece, Latvia, Poland, Switzerland and Turkey) to make a total of 29 partner organisations. A cluster of 65 additional organisations link, as local collaborators, to those partners.

Photonics4Life spans the value chain from photonic components to applications and from fundamental to applied research. It maps and networks R&D efforts to address:

- Analysis of cell processes;
- Micromanipulation and therapy;

[15] www.pianoplus.eu/
[16] www.olaeplus.eu/
[17] www.biophotonicsplus.eu

- Non- and minimally-invasive diagnosis and therapy; and
- Point-of-care diagnostics.

Although it is driven by academic institutes, P4L has close links to industry through its industrial user club (IUC), exchanging R&D results and undertaking joint activities such as projects. IUC companies have access to expertise and collaboration opportunities in P4L, as well as to information on P4L methodologies and technologies.

Source: Adapted from http://www.photonics4life.eu/P4L/About-Photonics4Life

European research is also being co-ordinated through collaboration on the development, establishing and running of large research infrastructures, so large that they cannot easily be funded by one agency or country alone. Under the auspices of the European Strategic Forum on Research Infrastructures (ESFRI)[18], Member States are coming together to fund infrastructures with EU grants supporting the preparatory phases of all selected projects. The EU funding portion is EUR 1.85 billion in FP7 and about EUR 2.5 billion in Horizon 2020 to photonics and other fields. Research infrastructures relevant to photonics include the Coordinated Access to Light-sources to Promote Standards and Optimisation (CALIPSO)[19]; The Integrated Initiative of European Laser Research Infrastructures III (LASERLAB EUROPE)[20]; and European Light Sources Activities – Synchrotrons and Free Electron Lasers (ELISA)[21] which all form part of the infrastructure needed to enable photonics applications of nanotechnology.

Other mechanisms to support research and innovation in nanotechnology and photonics are outlined in the section on 'Other EU Policies: Industry' later in this chapter. They include:

- EUREKA's Eurostars;
- European Technology Platforms; and
- Joint Technology Initiatives (and Joint Undertakings).

The next section reports on funding and participation data for the Sixth and Seventh EU Framework Programmes, FP6 and FP7.

3.2 The EU Framework Programme: funding and participation data for FP6 and FP7

3.2.1 Overview

Project-related Framework Programme (FP) data was extracted from the eCorda database for the EU Sixth Framework Programme (FP6) and the EU Seventh Framework Programme (FP7)[22]. The total number of projects was 35,265, of which 25,238 were FP7 projects and 10,027 were FP6 projects. There were 210,177 participations, of which 133,615 were in FP7 and 76,562 were in FP6.

From the initial set of 35,265 projects, 3,544 were found to be related to nanotechnology in that they contained the term "nano"[23] in the title or abstract of the project. Thus, nanotechnology projects form approximately 10% of the total FP projects. The share of nanotechnology projects increased slightly between FP6 (9.1%) and FP7 (10.4%).

74% of the 3,544 projects were FP7 projects and 26% were FP6 projects. The relative shares of nanotechnology projects were similar to those found for FP projects in general (72% in FP7 and 28% in FP6).

[18] http://ec.europa.eu/research/infrastructures/index_en.cfm?pg=home
[19] http://ec.europa.eu/programmes/horizon2020/en/news/biospecimens-beyond-borders
[20] http://www.spirit-ion.eu/Start.html
[21] http://www.qualitynano.eu/
[22] Data from eCorda extracted January 2015
[23] The term "nano" could appear as a part of a word (e.g. nanotechnology, nanoscience, nanomaterial, nanoscale), as a part of compound word separated with hyphen (e.g. nano-science) or as a separate word "nano".

Number and share of photonics nanotechnology projects

The number of projects (in FP6 and FP7 together) that were related to both photonics and nanotechnology was determined, using a keyword search[24], to be 483, 13.6% of the nanotechnology projects in the two Framework Programmes and 1.4% of overall projects in the FPs. The percentage of nanotechnology photonics (PH) projects was higher in FP7 at the time of extraction of the data (14.8% of total nanotechnology (NT) projects) than it was in FP6 (10.2% of total nanotechnology projects). This can be taken to be an indication that the relevance of photonics has increased within nanotechnology FP-activities from FP6 to FP7.

Table 3-1: Number of projects and shares for total projects, for NT and for PH

		Total	FP7	FP6
FP Total (FP)	Number of FP Projects	35,265	25,238	10,027
	Share of FP Projects (total)	100%	71.6%	28.4%
Nanotechnology (NT)	Number of FP Projects	3,544	2,636	908
	Share of FP Projects (NT)	100%	74.4%	25.6%
Share of Nanotechnology of Total FP (projects)		10.0%	10.4%	9.1%
Nanotechnology Photonics (PH)	Number of FP Projects	483	390	93
	PH share of NT Projects	13.6%	14.8%	10.2%
	PH share of FP Projects	1.4%	1.5%	0.9%

Funding of photonics nanotechnology projects

The 483 projects associated with nanotechnology photonics research and innovation activities received funding of EUR 737 million, equivalent to 11.6% of the funding for nanotechnology and 1.2% of the overall FP budget. In FP6, nanotechnology photonics research received 10.4% of nanotechnology funding and in FP7 it received 12.0% of the nanotechnology funding as shown in the figure below. Further details are given later in this section (see Activity by programme and sub-programme).

[24] See Annex for details of the keywords

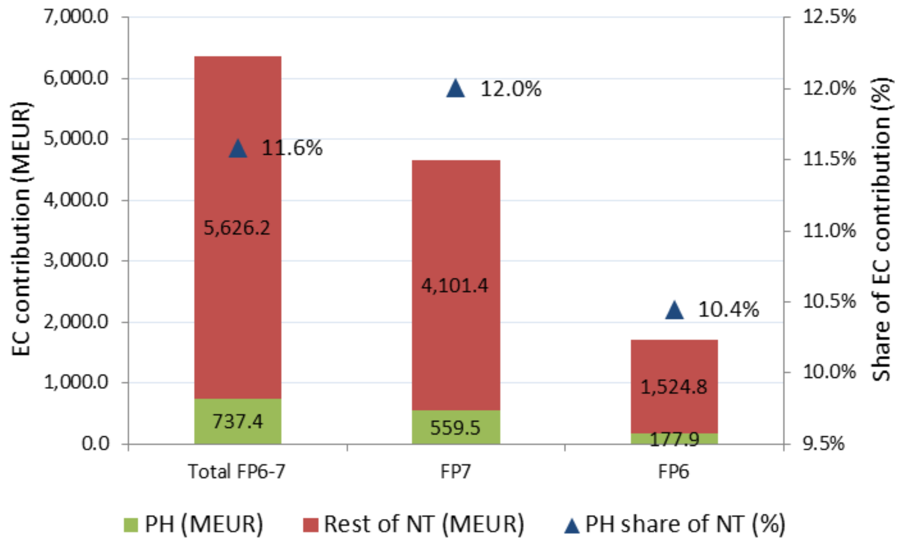

Figure 3-1: Share of EC funding for nanotechnology photonics projects for FP6 and FP7; FP7; and FP6

3.2.2 Activities by programme and sub-programme

3.2.2.1 FP6 photonics nanotechnology activities

FP6 was structured in three main blocks of activities[25]:

1. Focusing and integrating the ERA - divided into Thematic Priorities and Specific Activities;
2. Structuring the ERA – including research and innovation, research mobility, infrastructure development and science and society; and
3. Strengthening the ERA – for co-ordination and policy activities.

In FP6, the majority of the activities specific to nanotechnology and photonics (51 projects) took place under the activity of Focusing and integrating the ERA, while the remainder (42) took place under Structuring the ERA. Within the actions for Focusing and Integrating the ERA:

- NMP (Nanotechnologies and nanosciences, knowledge based multi-functional materials and new production processes and devices) had the largest number of nanotechnology photonics projects (32) and a total of EUR 92.8 million of EC funding (52.1% of the total for nanotechnology photonics); and
- Information Society Technologies (IST) had 15 projects and EUR 40.3 million of EC funding (22.7% of total).

These two Thematic Priorities thus took almost 75% of the total budget for nanotechnology photonics in FP6. One project on Sustainable Development received almost 5% of the budget (EUR 8.3 million).

Under the actions for Structuring the ERA, Human Resources and Mobility received 16.7% of the budget (EUR 29.7 million).

[25] There was, in addition, the EURATOM activity.

Table 3-2: FP6 nanotechnology photonics projects by programme and sub-programme

FP6 Summary of activities	Number of projects			EC contribution (MEUR)			Share of EC contribution		
	FP6	FP6 NT	FP6 PH	FP6	FP6 NT	FP6 PH	FP6	FP6 NT	FP6 PH
I Focussing and integrating ERA	**4,735**	**455**	**51**	**13,445.0**	**1,383.6**	**145.8**	**80.5%**	**81.3%**	**81.9%**
Thematic priorities	3,374	389	48	12,027.5	1,314.8	141.4	72.1%	77.2%	79.5%
1. Life sciences	602	20	0	2,336.5	54.1	0.0	14.0%	3.2%	0.0%
2. Information society	1,089	80	15	3,798.9	346.1	40.3	22.8%	20.3%	22.7%
3. NMP	444	271	32	1,534.2	870.1	92.8	9.2%	51.1%	52.1%
4. Aeronautics and space	241	5	0	1,066.1	11.6	0.0	6.4%	0.7%	0.0%
5. Food quality and safety	189	0	0	754.2	0.0	0.0	4.5%	0.0%	0.0%
6. Sustainable development	666	10	1	2,300.9	30.5	8.3	13.8%	1.8%	4.7%
7. Citizens and governance	143	3	0	236.6	2.4	0.0	1.4%	0.1%	0.0%
Specific activities	1,361	66	3	1,417.5	68.8	4.4	8.5%	4.0%	2.5%
Policy support	520	29	2	604.2	40.7	3.4	3.6%	2.4%	1.9%
Horizontal research involving SMEs	490	29	1	463.1	24.7	1.0	2.8%	1.4%	0.5%
International cooperation	351	8	0	350.3	3.4	0.0	2.1%	0.2%	0.0%
II Structuring the European Research Area	**5,096**	**449**	**42**	**2,744.2**	**303.1**	**32.1**	**16.4%**	**17.8%**	**18.1%**
Research and innovation	240	3	1	224.0	3.9	0.9	1.3%	0.2%	0.5%
Human resources and mobility	4,546	420	40	1,723.1	219.2	29.7	10.3%	12.9%	16.7%
Research infrastructures	147	17	1	717.6	74.3	1.6	4.3%	4.4%	0.9%
Science and society	163	9	0	79.5	5.8	0.0	0.5%	0.3%	0.0%
III Strengthening ERA	118	3	0	317.3	8.0	0.0	1.9%	0.5%	0.0%
Coordination of activities	99	3	0	303.8	8.0	0.0	1.8%	0.5%	0.0%
Research & innovation policies	19	0	0	13.5	0.0	0.0	0.1%	0.0%	0.0%
EURATOM	78	1	0	185.7	8.0	0.0	1.1%	0.5%	0.0%
TOTAL	10,027	908	93	16,692.3	1,702.7	177.9	100.0%	100.0%	100.0%

3.2.2.2 FP7 photonics nanotechnology activities

The broad objectives of FP7 group into four categories:

- Co-operation;
- Ideas;
- People; and
- Capacities.

In FP7, the largest proportion of activities specific to nanotechnology and photonics took place under Co-operation, with 79 projects and EUR 270.4 million (48.3% of funding). Within Co-operation:

- ICT had the largest number of nanotechnology photonics projects (46) and a total of EUR 130.7 million of EC funding (23.4% of the total for nanotechnology photonics); and
- NMP (for Nanosciences, nanotechnologies, Materials and new Production technologies) had all but seven of the remaining Co-operation projects – 26 projects, EUR 111.1 million of

funding (19.9% of nanotechnology photonics FP7 funding).

Table 3-3: FP7 nanotechnology photonics projects by programme and sub-programme

FP7 Summary of Activities	Number of Projects			EC Funding (MEUR)			Share of EC Funding		
	FP7	FP7 NT	FP7 PH	FP7	FP7 NT	FP7 PH	FP7	FP7 NT	FP7 PH
CO-OPERATION	7,834	756	79.0	28,336.3	2,803.8	270.4	63.1%	60.2%	48.3%
Health	1,008	33	1	4,791.7	157.0	5.9	10.7%	3.4%	1.1%
Food, Agri and Bio	516	25	1	1,850.7	97.1	3.0	4.1%	2.1%	0.5%
ICT	2,328	175	46	7,877.0	561.3	130.7	17.5%	12.0%	23.4%
NMP	805	412	26	3,238.6	1,595.6	111.1	7.2%	34.2%	19.9%
Energy	368	24	2	1,707.4	81.5	5.9	3.8%	1.7%	1.1%
Environment	494	10	0	1,719.3	26.9	0.0	3.8%	0.6%	0.0%
Transport	719	12	0	2,284.2	61.5	0.0	5.1%	1.3%	0.0%
Socio-economic sciences	253	0	0	579.6	0.0	0.0	1.3%	0.0%	0.0%
Space	267	14	1	713.3	31.7	1.5	1.6%	0.7%	0.3%
Security	314	5	1	1,295.5	14.1	3.4	2.9%	0.3%	0.6%
General Activities	26	0	0	312.7	0.0	0.0	0.7%	0.0%	0.0%
Joint Technology Initiatives	736	46	1	1,966.4	177.0	8.8	4.4%	3.8%	1.6%
IDEAS	4,525	572	102	7,673.5	1,026.1	173.4	17.1%	22.0%	31.0%
European Research Council	4,525	572	102	7,673.5	1,026.1	173.4	17.1%	22.0%	31.0%
PEOPLE	10,716	1,158	198	4,777.5	579.9	103.7	10.6%	12.4%	18.5%
Marie-Curie Actions	10,716	1,158	198	4,777.5	579.9	103.7	10.6%	12.4%	18.5%
CAPACITIES	2,025	149	11	3,772.0	249.9	12.0	8.4%	5.4%	2.1%
Research Infrastructures	341	18	1	1,528.4	72.2	1.0	3.4%	1.5%	0.2%
Research for the benefit of SMEs	1,028	70	3	1,249.1	86.1	4.4	2.8%	1.8%	0.8%
Regions of Knowledge	84	4	0	126.7	7.3	0.0	0.3%	0.2%	0.0%
Research Potential	206	27	3	377.7	55.1	4.6	0.8%	1.2%	0.8%
Science in Society	183	16	0	288.4	16.5	0.0	0.6%	0.4%	0.0%
Research policies	26	0	0	28.3	0.0	0.0	0.1%	0.0%	0.0%
International Cooperation	157	14	4	173.4	12.7	2.0	0.4%	0.3%	0.4%
EURATOM	138	1	0	358.1	1.1	0.0	0.8%	0.0%	0.0%
Fusion	4	0	0	5.2	0.0	0.0	0.0%	0.0%	0.0%
Fission	134	1	0	352.8	1.1	0.0	0.8%	0.0%	0.0%
TOTAL	25,238	2,636	390	44,917.3	4,660.8	559.5	100.0%	100.0%	100.0%

Under Ideas, the European Research Council activities have 31% of the funding (EUR 173.4 million) and 102 projects. Marie Curie Actions (People) are responsible for most of the remaining funding with 18.5% of the nanotechnology photonics total (EUR 103.7 million) and 198 projects.

3.2.3 Activities by participant type

The table below shows the participations in FP6 and FP7 for the Higher Education Sector (HES), other research organisations (RECs), large companies (PCO), SMEs and other organisations. As well as the number of participations (Particip.), the table shows the total EC funding and share of funding for each, for all FP6 and FP7 and for NT and nanotechnology photonics.

Table 3-4: Participations in FP6 and FP7 including funding and shares of funding[26]

	Total FP6 and FP7			NT in FP6 and FP7			NP in FP6 and FP7		
	Particip.	EC Funding	Share of Funding	Particip.	EC Funding	Share of Funding	Particip.	EC Funding	Share of Funding
HES	76,777	25,736.0	41.8%	7,671	3,019.5	47.5%	992	406.8	55.2%
REC	53,384	17,304.4	28.1%	4,696	1,778.1	28.0%	487	226.4	30.7%
PCO	25,067	7,021.3	11.4%	2,275	615.4	9.7%	152	42.9	5.8%
SME	29,428	6,882.6	11.2%	3,239	769.1	12.1%	187	51.6	7.0%
Other	24,961	4,626.8	7.5%	1,059	174.2	2.7%	64	9.8	1.3%
Total	209,617	61,571.1	100.0%	18,940	6,356.2	100.0%	1,882	737.5	100.0%

In nanotechnology photonics (PH), the participants receiving most EC funding are higher education organisations with 55.2% of the total funding for nanotechnology photonics activities. This share is slightly higher than the one received by these organisations for NT activities (47.5%) and FP activities in general (41.8%). The participants receiving the second highest proportion of funding for PH activities are research organisations with 30.7% of the total funding for nanotechnology photonics. This share is again higher than the share of funding received by research organisations for both nanotechnology activities and FP activities in general (28% and 28.1% respectively).

Companies (both large companies and SMEs) receive a lower share of funding (12.8%) for nanotechnology photonics than they do in nanotechnology (21.8%) and in FP overall (22.6%). Thus, the participant data indicates that nanotechnology photonics FP activities are still rather oriented to (basic) research and less to development activities closer to the market.

Table 3-5: EC funding and share of funding by organisation type (FP6 and FP7)

Type of Organisation	EC Funding (MEUR)	Share of EC Funding (%)
Higher Education	406.8	55.2%
Research Organisation	226.4	30.7%
Large Company	42.9	5.8%
SME	51.6	7.0%
Other (including N/A)	9.8	1.3%
Total	737.5	100.0%

As seen from the figure below, the funding shares are similar for FP6, FP7 and the two FPs together. The share for higher education increased slightly from FP6 (54.8%) to FP7 (55.3%) while the share

[26] The EC contribution in eCorda project and participant database differ by a small amount. The figures reported here for participants therefore do not exactly match those for projects in previous sections.

for research organisations (REC) decreased (31.3% in FP6 and 30.5% in FP7). The company share increased, mainly due increased participation of SMEs (4.2% in FP6 and 7.9% in FP7), although the overall company participation remains at a rather modest level for the two FPs together (12.8%).

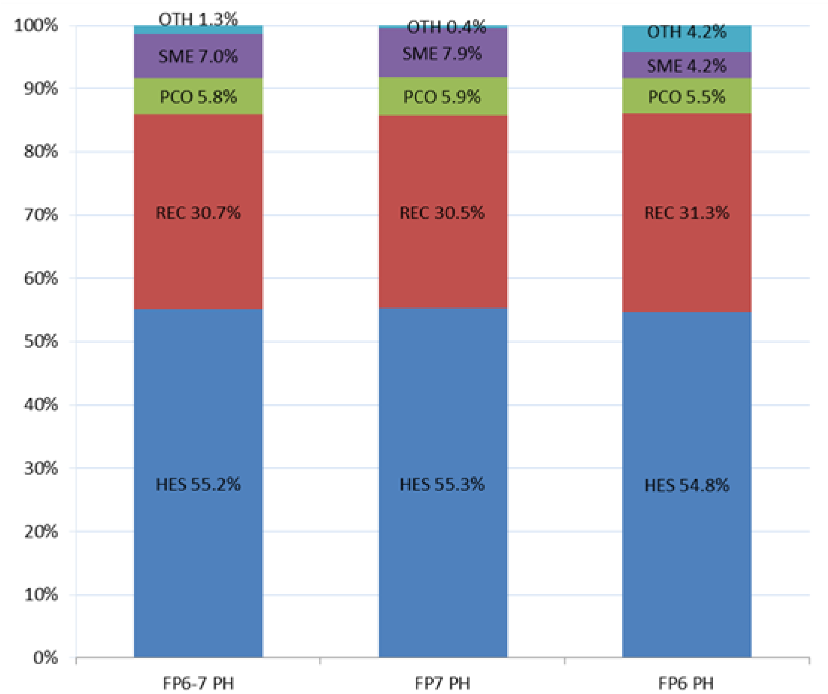

Figure 3-2: Shares of EC funding by organisation type for nanotechnology photonics

3.2.4 Activity by organisations receiving funding

The table below shows that nanotechnology photonics FP6-7 research is dominated by large research organisations and universities. Six of the top ten organisations receive most of the funding and the top three of those are research organisations, not universities.

The CNRS (FR) receives the largest amount of funding, EUR 34.5 million, in 64 projects. It is followed by CEA (FR) (EUR 28 million, 32 projects) and CNR (IT) (EUR 15 million, 39 projects). Imperial College (UK) is the highest placed higher education institute (EUR 14 million, 20 projects), followed by the University of Cambridge (EUR 13.7 million, 24 projects).

Table 3-6: Organisations participating in FP6 and FP7, top 25 ranked by funding received

	Photonics - Top Participants	Country	No. of projects	EC funding (MEUR)	Share of PH funding
1	CNRS[27]	FR	64	34.46	4.67%
2	CEA[28]	FR	32	27.77	3.77%
3	CNR[29]	IT	39	15.28	2.07%
4	Imperial College	UK	20	14.01	1.90%
5	University of Cambridge	UK	24	13.72	1.86%
6	Fundacio Institut de Ciencies Fotoniques	ES	22	12.37	1.68%
7	Max Planck Gesellschaft	DE	18	12.17	1.65%
8	EPFL[30]	CH	35	11.70	1.59%
9	Chalmers Tekniska Hoegskola AB	SE	22	11.42	1.55%
10	Fraunhofer[31]	DE	22	10.11	1.37%
11	University College Cork	IE	18	9.73	1.32%
12	CSIC[32]	ES	21	9.53	1.29%
13	Technion Israel Institute Y Technology	IL	16	9.40	1.28%
14	IMEC[33]	BE	17	7.95	1.08%
15	KTH[34]	SE	14	7.66	1.04%
16	ETHZ[35]	CH	11	7.62	1.03%
17	University of Southampton	UK	18	7.56	1.03%
18	University of Oxford	UK	8	7.30	0.99%
19	Technische Universiteit Delft	NL	14	7.21	0.98%
20	University of Dundee	UK	4	7.18	0.97%
21	Universiteit Gent	BE	9	6.61	0.90%
22	Foundation for Research and Technology Hellas	EL	12	6.42	0.87%
23	Ludwig-Maximilians-Universitaet Muenchen	DE	8	6.31	0.86%
24	FOM[36]	NL	5	6.18	0.84%
25	VTT[37]	FI	9	5.95	0.81%

The table below indicates the most active companies in FP nanotechnology photonics projects. Company participation is rather modest in this area of research. The company receiving the most funding, S.O.I. Tec Silicon on Insulator Technologies SA (FR), participated in only one project, receiving funding of EUR 5.6 million, and is only in 27th position in the overall list of nanotechnology

[27] Centre National de la Recherche Scientifique, the National Centre for Scientific Research www.cnrs.fr
[28] Commissariat à l'Énergie Atomique et aux Énergies Alternatives, the French Alternative Energies and Atomic Energy Commission www.cea.fr
[29] Consiglio Nazionale Delle Ricerche, the Italian National Research Council www.cnr.it
[30] École Polytechnique Fédérale de Lausanne, the Swiss Federal Institute of Technology in Lausanne www.epfl.ch
[31] Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. www.fraunhofer.de
[32] Consejo Superior de Investigaciones Cientificas, the Spanish National Research Council www.csic.es
[33] Interuniversitair Micro-Elektronica Centrum Vzw, www.imec.be
[34] Kungliga Tekniska Hoegskolan https://www.kth.se/en
[35] Eidgenoessische Technische Hochschule Zuerich https://www.ethz.ch/en.html
[36] Stichting Voor Fundamenteel Onderzoek der Materie https://www.fom.nl/en/
[37] Teknologian Tutkimuskeskus http://www.vttresearch.com/

photonics FP participants. It was the co-ordinator for the JTI project AGATE-Development of Advanced GaN Technologies. IBM Research GmbH (CH) is in second place among the companies but in 48th position in nanotechnology photonics FP overall. It took part in ten projects (EUR 3 million. These first two companies are followed by Aixtron SE (DE), Philips Electronics Nederland (NL) and Thales SA (FR).

Table 3-7: Companies participating in FP6 and FP7, top 25 ranked by funding received

	Photonics - Top Company Participants	Country	SME	No. of Projects	EC Funding (MEUR)
1	Silicon on Insulator Technologies SA	FR		1	5.60
2	IBM Research GmbH	CH		10	3.02
3	Aixtron SE	DE		7	2.70
4	Philips Electronics Nederland B.V.	NL		7	2.51
5	Thales SA	FR		9	2.11
6	BASF SE	DE		6	1.69
7	Innolume GmbH	DE		3	1.67
8	STMicroelectronics SRL	IT		5	1.58
9	Microfluidic Chipshop GmbH	DE	SME	3	1.22
10	Scriba Nanotecnologie SRL	IT	SME	3	1.19
11	ON Semiconductor Belgium BVBA	BE		1	1.13
12	Philips Technologie GmbH	DE		3	1.11
13	Toptica Photonics AG	DE	SME	2	1.08
14	Integra Renewable Energies SRL	IT	SME	1	1.00
15	Tescan Orsay Holding AS	CZ	SME	1	0.98
16	Osram Opto Semiconductors GmbH	DE		3	0.97
17	Obducat Technologies AB	SE	SME	2	0.90
18	Mantis Deposition Limited	UK	SME	2	0.89
19	Xenics nv	BE	SME	2	0.89
20	Micro Resist Technology GmbH	DE	SME	4	0.88
21	UAB Modernios E-Technologijos	LT	SME	1	0.87
22	Profactor GmbH	AT	SME	2	0.85
23	Modulight OY	FI	SME	3	0.85
24	BASF Schweiz AG	CH		1	0.83
25	JDSU Ultrafast Lasers AG	CH	SME	2	0.82

In general, large companies are in the top positions in the list of the 25 largest funding received by companies although approximately half of the companies in the list are SMEs. The SME that received most funding from PH FP6-7 was Microfluidic ChipShop GmbH from Germany (3 projects and EUR 1.2 million), followed by the Italian company Scriba Nanotechnologie SRL (3 projects, EUR 1.2 million) and Toptica Photonics AG from Germany (2 projects, EUR 1.1 million). It should however be noted that many of the companies in the list are participating only in one or two projects.

3.2.5 Participation by country

The table below shows the EC funding distribution in terms of millions of euro allocated to each country, a ranking of countries in terms of funding and the country shares of funding in nanotechnology photonics, nanotechnology and FP.

Participants from 45 countries took part in nanotechnology photonics projects under FP6 and FP7. Looking at the countries of origin of these participants, the list is headed by Germany, the United Kingdom and France, the same three countries that also received the most funding under FP6 and FP7 in general. The participation in nanotechnology photonics is heavily concentrated in five countries that received nearly two thirds of the total funding for nanotechnology photonics activities. These five countries are: Germany (17.9%), the United Kingdom (15.7%), France (13.8%), Spain (8.1%) and Italy (8%).

Regarding country specialisation in photonics in total FP activities, the countries with the highest proportion of their total FP funding dedicated to photonics are Lithuania (3.7%, EUR 3 million), Ireland (1.9%, EUR 15.3 million), Turkey (1.8%, EUR 4.4 million), Switzerland (1.6%, EUR 40.5 million), France (1.4%, EUR 101.8 million) and Spain (1.4%, EUR 59.5 million). However, out of these countries, Lithuania and Turkey received relatively low nanotechnology photonics funding.

Table 3-8: Top fifteen countries for FP participation ranked by funding received for nanotechnology photonics

Rank	Country	Nanotechnology Photonics Funding (MEUR)	% of Funding
1	DE	132.3	17.9%
2	UK	115.8	15.7%
3	FR	101.8	13.8%
4	ES	59.5	8.1%
5	IT	58.9	8.0%
6	NL	41.1	5.6%
7	CH	40.5	5.5%
8	SE	28.5	3.9%
9	BE	27.5	3.7%
10	EL	16.3	2.2%
11	IE	15.3	2.1%
12	AT	14.0	1.9%
13	FI	13.9	1.9%
14	IL	13.3	1.8%
15	DK	13.3	1.8%
	TOTAL	**692**	**93.9%**

As shown in the figure below, Germany, the United Kingdom, France, Spain and Switzerland are the top participant countries that are more active in nanotechnology photonics than in nanotechnology or FP overall. The Netherlands is less active in nanotechnology photonics than in nanotechnology or FP overall, as is Belgium. This may reflect the emphasis in those countries on the more industrial end of the research and development scale, with the Dutch NanoNextNL and the Belgian centre IMEC[38].

[38] Interuniversitair Micro-Elekctronica Centrum Vzw

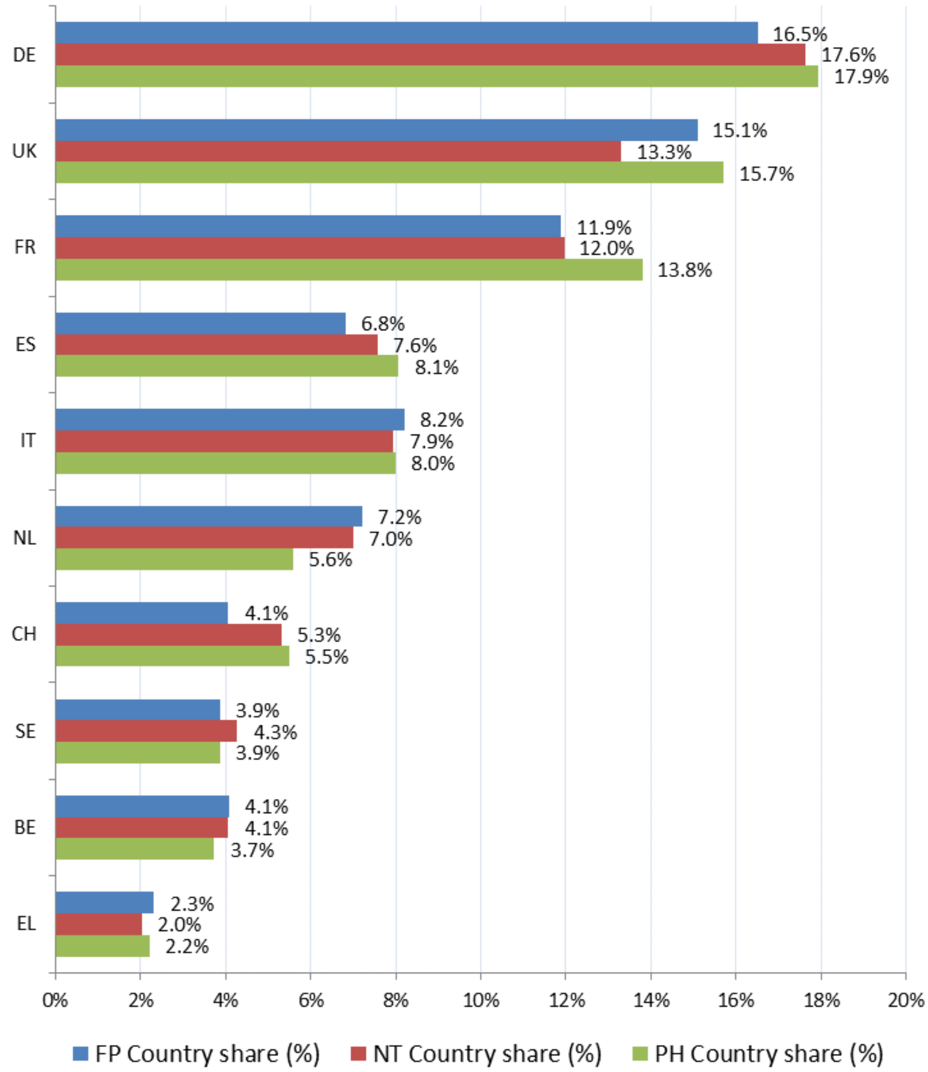

Figure 3-3: Percentage shares of FP funding by country in FP, NT and nanotechnology photonics

The figure below indicates the EC funding for nanotechnology photonics activities in FP6 and FP7 in terms of MEUR (bars, use left axis) and country shares (dots, use right axis) for the ten countries receiving the most funding. The country shares of nanotechnology photonics funding increased for most countries, for example, Germany (an increase of 3.4%), United Kingdom (an increase of 3.2%) or Belgium (an increase of 2.6%). Three countries experienced a significant decrease in the share of funding devoted to nanotechnology photonics: Sweden (2.6% decrease), Spain and Italy (both with 1.9% decrease).

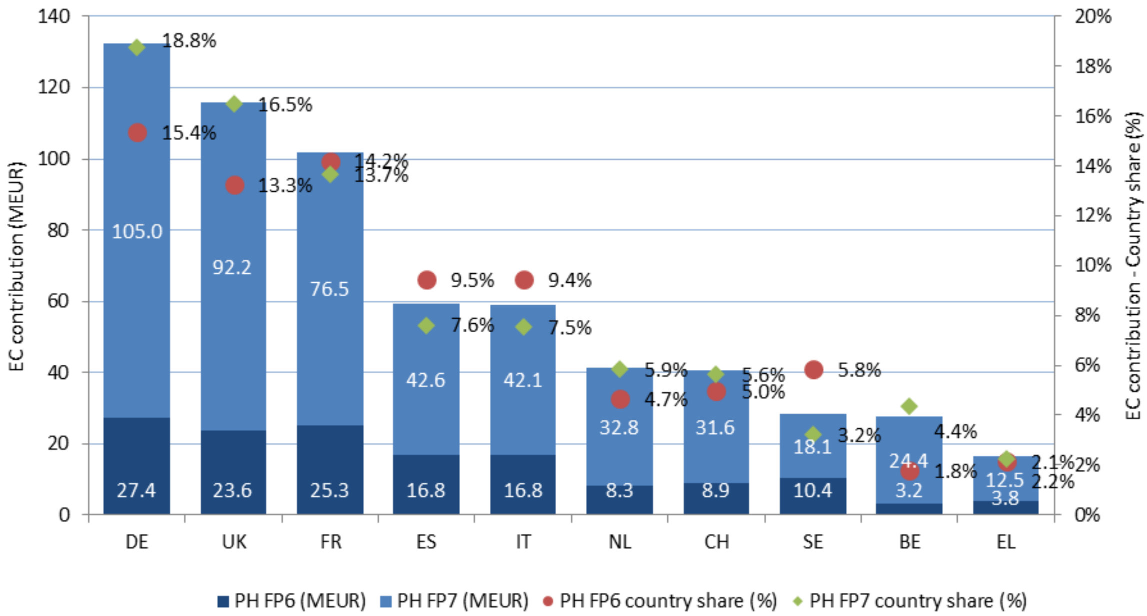

Figure 3-4: EC funding for nanotechnology photonics in FP6 and FP7 in MEUR and country shares

3.2.6 Snapshot of outputs from FP7

A review was undertaken of 106 FP7 nanotechnology projects reported on via the SESAM system in which participants report themselves on their project. The projects are random, being the first ones to report, which they can only do when the project has finished. In addition, the information has not been normalised to take into account the type and size of project. It is therefore not intended here to present the information as a rigorous review, only as a snapshot at a point in time of FP7 projects that have reported to date.

In the review of the 106 SESAM report, it was found that:

- 82% of projects had published work during the project, the total number of publications being 1783 and the average number being almost 17; and
- 32% of projects had applied for patents, a total of 73 patents having been applied for, an average of 0.7 per project. Of these, 18 have been applied for at the European Patent Office, 20 under the PCT at WIPO, 6 at the USPTO and 30 at other (national) patent offices.

Of the 106 projects, ten were classified by review as being related to photonics nanotechnology. Those ten projects reported outputs of:

- 288 publications, an average of almost 29 publications per project, much higher than for nanotechnology overall; and
- 6 patent applications, an average of 0.6 per project, less than for nanotechnology overall.

Thus, of the projects under review, photonics nanotechnology projects under FP7 produce more than the average number of publications and less than the average number of patents per project than for nanotechnology overall.

The next section considers EU policies and programmes that complement the supports for nanotechnology and photonics described previously in this section for the EU Framework Programmes.

3.3 Other EU policies and programmes

Rare-earth material supplies and photonics

One issue of concern for the photonics industry that is not specifically related to nanotechnology is the availability of rare-earth materials[39]. These are 17 chemical elements (the fifteen lanthanides (e.g. cerium, holmium and erbium) plus scandium and yttrium) that tend to be widely dispersed in the Earth's crust and are not easy to find in large quantities in mineral form.

There is a scarcity of these materials within the EU and elsewhere resulting in a high global dependency on China (the main supplier of rare-earth materials). That dependence on China was exacerbated by restrictions on the export of various forms of rare earths, as well as tungsten and molybdenum, applied by the Chinese Government.

In its Communication on tackling the challenges in commodity markets (2011), the European Commission published a list of 14 Critical Raw Materials (CRMs), including rare-earths jointly as one CRM, selected according two criteria: economic importance and supply risk[40]. The list had 3 main objectives: (i) to implement EU's industrial policy and strengthen industrial competitiveness; (ii) to stimulate the production of CRMs and the launch of new mining activities in the EU; and (iii) to prioritise actions, negotiate trade agreements, challenge trade distortion measures, and promote research and innovation.

Given their crucial importance in modern technology, in 2012, a group representing the EU Member States, the United States, Japan and other countries brought the Chinese trading restrictions to the attention of the Dispute Settlement Body of the World Trade Organisation (WTO). It was not until March 2015 that, finding them to be inconsistent with WTO rules, the application of export duties and export quotas to rare earths, tungsten and molybdenum, as well as restrictions on the trading rights of exporters of rare earths and molybdenum, were lifted.

The European list of Critical Raw Materials was revised in 2014 from 14 to 20 CRMs[41] included in the Communication: 'On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative'[42].

3.3.1 EU policies and programmes: Industry

Policies related to industry and economic development fall under the Framework Programmes (e.g. for ICT) and other EU measures (e.g. under the remit of DG Enterprise and Industry).

In September 2009, the European Commission designated photonics as one of six Key Enabling Technologies for our future prosperity[43]. Key Enabling Technologies (KETs)[44] are a priority for European industrial policy. The European Strategy for KETs aims to increase the exploitation of KETs in the EU and to reverse the decline in manufacturing to stimulate growth and jobs. The European

[39] http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/

[40] The CRMs are critical because of the risks of supply shortage and because their impacts on the economy are higher than most other raw materials. The risk is due to production being mainly in only a handful of countries: China (antimony, fluorspar, gallium, germanium, graphite, indium, magnesium, rare earths, tungsten), Russia (platinum group metals), the Democratic Republic of Congo (cobalt, tantalum) and Brazil (niobium and tantalum), and due to their low substitutability and low recycling rates. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0025

[41] China is the most influential country in terms of global supply of the 20 critical raw materials. Several other countries have dominant supplies of specific raw materials, such as Brazil (niobium). http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm

[42] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0297

[43] COM(2009) 512 final of 30 September 2009

[44] KETs are: Advanced Materials, Nanotechnology, Nano & Microelectronics, Photonics, Biotechnology and Advanced Manufacturing

Commission tabled (26 June 2012) its strategy to boost the industrial production of KETs-based products, e.g. innovative products and applications of the future. The strategy aims to keep pace with the EU's main international competitors, restore growth in Europe and create jobs in industry, at the same time addressing today's burning societal challenges. The European Commission has identified KETs as a key priority within its Europe 2020 strategy. KETs are seen as essential to flagship initiatives such as Innovation Union and Digital Agenda for Europe.

Research by companies in the EU is also supported through the EUREKA Eurostars[45] initiative established under Article 185 of the Treaty on the Functioning of the European Union, in partnership between the European Commission, the Member States and the countries associated with the Framework Programmes. Eurostars supports European R&D performing SMEs to commercialise their research. It helps them to accelerate the time to market of products, processes and services to the market. It also encourages them to develop and internationalise their business. Funding of up to EUR 100 million was made available through EUREKA for the period 2008-2013, the EU contribution comprising a maximum of one third of the funding provided by the participating countries. Funding for Eurostars has continued with a total public budget of EUR 1.14 billion in 2014-2020, EUR 861 million of national funding and EUR 287 million of EU funding from Horizon 2020. In the 39 success stories identified for Eurostars, two are related to nanotechnology.

Another type of mechanism is the European Technology Platform (ETP) including the European Technology Platform Photonics21. ETPs are bottom-up, industry-led stakeholder fora, the aim of which is to increase interaction between research actors and to facilitate the development of medium to long-term research and technological goals and associated roadmaps. They do not fund research projects but are a co-ordination mechanism. ETPs now exist across the themes of energy, environment, ICT, production and processes, transport and the bio-based economy. Photonics21 sits under the theme of ICT. There are seven priority areas (e.g. working groups): Information and Communication; Industrial Manufacturing and Quality; Life Sciences and Health; Emerging Lighting, Electronics and Displays; Security, Metrology and Sensors; Design and Manufacturing of Components and Systems; Photonics Research, Education and Training.

Joint Technology Initiatives (JTIs) are long-term Public-Private Partnerships managed within dedicated structures based on Article 187 of the Treaty on the Functioning of the European Union (TFEU). JTIs support large-scale multinational research activities in areas of major interest to European industrial competitiveness as well as issues of high societal relevance. They are established on the basis of European Technology Platforms (ETPs) in those cases where the scale and scope of the initiatives make insufficient their co-ordination through ETPs and support by the regular instruments of the Framework Programme for Research and Development[46] alone. Six areas were identified for the development of a JTI: Nano-electronics (ENIAC)[47]; Innovative Medicines; Fuel Cells and Hydrogen; Embedded Computing Systems; Aeronautics; and GMES (global monitoring for environment and security).

ENIAC[48], the JTI in the area of nano-electronics, has long operated across electronics including photonics and has funded projects of interest to the photonics industry[49]. The ENIAC Joint Undertaking was established in 2008 to co-ordinate European nano-electronics research activities through competitive calls for proposals. It describes itself as a public-private partnership in nano-electronics strengthening European competitiveness and sustainability, bringing together the ENIAC member states, the European Commission and AENEAS, the association of R&D actors in the field.

ECSEL, the Joint Technology Initiative for Electronic Components and Systems for European Leadership[50] is the public-private partnership in electronic components and systems, covering the topics addressed in FP7 within the ARTEMIS and the ENIAC JTIs and in the ETP EPoSS. Its consortia are collaborating on projects to develop smart systems, systems and components for smart energy, smart cities, smart governance and smart living, including photonics. The current members of ECSEL

[45] https://www.eurostars-eureka.eu/
[46] http://era.gv.at/directory/142
[47] Since 2014, ENIAC and ARTEMIS has been replaced by ECSEL (https://ec.europa.eu/digital-agenda/en/time-ecsel)
[48] http://www.eniac.eu/web/index.php
[49] http://www.swissphotonics.net/libraries.files/ECSEL_JU_and_Photonics_Overview.pdf
[50] http://www.ecsel-ju.eu/web/index.php

are the European Union (through the Commission); Member States and Associated Countries to Horizon 2020; and three associations (EPoSS[51], AENEAS and the ARTEMIS Industry Association) representing the actors from the areas of micro- and nano-electronics, smart integrated systems and embedded/cyber-physical systems.

In 2013, under Horizon 2020, the European Commission launched the contractual Public Private Partnerships (cPPPs) to leverage more than EUR 6 billion of investments through H2020 calls. One of the eight cPPS is on Photonics[52] and grew out of the Photonics21 ETP (which is now the cPPP's private partner mechanism). It has an allocated budget of EUR 700 million in H2020 (EUR 156 million in 2014-2015) and an expected industry investment of EUR 2,800 million[53]. The PPP is based on the seven-year Multiannual Strategic Roadmap – Towards 2020 – Photonics Driving Economic Growth in Europe, which underpins the proposed activities to grow photonics manufacturing and employment.

Photonics21 - The European Technology Platform for Photonics

Established in 2005, the European Technology Platform Photonics21 is based on a personal membership and has currently 2,781 members, the majority of the leading photonics industries and relevant R&D stakeholders along the whole economic value chain throughout Europe. It seeks to establish Europe as a leader in the development and deployment of photonics technologies within application fields such as ICT, lighting, industrial manufacturing, life science, safety as well as in education and training.

Photonics21 coordinates photonics research and innovation priorities, providing input to the European Eighth European Framework Programme for Research & Innovation, Horizon 2020. Effective November 2013, the "Photonics 21 Association" (a legal entity under Belgium law) was formed to become the private contract partner in a contractual Public Private Partnership (cPPP) arrangement with the EU Commission in the context of Horizon 2020.

Many important European industries, from chip manufacturing and lighting, health-care and life sciences, to space, defence and the transport and automotive sectors rely on photonics. In striving to achieve leadership in the field for Europe, an ambitious programme has been laid out to:

- Supply the necessary research environment capable of supporting R&D activities for photonics components, systems and their application over a broad range of industry sectors;
- Establish strategic links between mainly SME-based photonics industries and principal user industries to share their long term vision and to mobilise a critical mass resources; and
- Foster co-operation and remove any fragmentation of national and European R&D activities.

Source: Adapted from http://www.phorce21.org/, http://www.photonics21.org/

3.3.2 EU policies and programmes: Structural and Investment Funds

Four (out of five) European Structural and Investment Funds (ESI Funds) provide support for research and innovation activities:

- The European Regional Development Fund (ERDF), for economic regeneration and safeguarding employment. Its main priorities are the support of small to medium-sized enterprises (of which there are many in photonics-related areas); the creation of a low carbon economy; research and innovation; information and communications technology (including photonics); environmental protection, climate change adaptation, risk prevention and management, transport and social inclusion.

[51] http://www.smart-systems-integration.org/public
[52] http://ec.europa.eu/research/press/2013/pdf/ppp/photonics_factsheet.pdf
[53] Ibid

- The European Social Fund (ESF), for the enhancement of employment opportunities, social inclusion and skills. Across all sectors, it supports skills and training; access to employment for all including women and migrants; improvement of public services; innovation in SMEs and access to start-up capital.

The ERDF and ESF together have a budget of about EUR 280 billion over 2014-2020.

- The European Agricultural Fund for Rural Development (EAFRD), which aims to strengthen the links between agriculture, food production and forestry and those performing research and innovation activities. Groups of collaborators are funded under the European Innovation Partnership on Agricultural Productivity and Sustainability. The Fund has a budget of EUR 95.6 billion over 2014-2020.
- The European Maritime and Fisheries Fund (EMFF) with a budget of EUR 6.4 billion over 2014-2020 for the development of businesses through research and innovation. It can also fund research studies for the development of policies for the management of fisheries.

3.3.3 EU policies and programmes: Cohesion funds

SMART SPECIALISATION AND REGIONAL RDI POLICY

The European Commission's Cohesion Policy aims to reduce differences between regions in Europe and to ensure growth across the continent. Structural Funds are among the main tools to implement the policy, and it is within this framework that smart specialisation was introduced. The Smart Specialisation Strategies (RIS3) [54] are agendas for transformation that aims to focus regional innovation policies on regional priorities based on existing areas of strength, competitive advantage, and potential for excellence in each region.

Smart Specialisation is about identifying the unique characteristics and assets of each country and region, highlighting each region’s competitive advantages, and aligning the regional stakeholders and resources around an excellence-driven vision of their future. It is an integrated agenda that:

- focuses policy support and investments on key national/regional priorities and challenges;
- builds on each country/region’s strengths, competitive advantages and potential for innovation excellence and exploits potential synergies with other countries and regions; and
- supports all forms of innovation, encourages innovation and experimentation and aims to stimulate private sector investment;

The next section looks at Member State supports for research and innovation on photonics and nanotechnology.

[54] http://s3platform.jrc.ec.europa.eu/eye-ris3. As of December 2015, 260 regions and countries that prioritise KETs; out of these there are 7 regions that have set a priority in nanotechnology.

4 POLICIES AND PROGRAMMES IN MEMBER STATES FOR NANOTECHNOLOGY AND PHOTONICS

While European funding is important for many researchers, it makes up only about 8% of total public funding for R&D in the European Union. Member States channel the remaining 92% into national research and development, mostly retaining it within their own borders. However, much of that funding is employed in projects the results of which feed into European networks and collaborations. As Member States chose to prioritise nanosciences and nanotechnologies for funding at European level, it is hardly surprising that they largely have the same view at national level, funding nanotechnology R&D either as a designated priority area or within broader programmes.

For photonics, specific initiatives at Member State level, past[55] or present, include:

- The Austrian NanoInitiative[56] (2004-2011, total funding EUR 70 million, administered by the Austrian Research Promotion Agency (FFG)), nanotechnology and photonics being one of nine priority areas. The initiative worked on a collaborative basis across Austria and transnationally with consortia of research institutes, universities and firms working on problem-driven basic research questions with a medium-term perspective (5-7 years). The focus of the programme, matching the remit of its funding agency FFG, was to invest in projects with considerable market potential, relevant to Austrian companies. The type of activities begun under the programme, are now continuing under the thematic areas FFG's research funding programmes.
- NanoNed (2004 – 2010, total funding of EUR 235 Million administered by the Dutch Ministry for Economic Affairs), the Nanotechnology R&D initiative in the Netherlands has clustered the Dutch expertise on nanotechnology and enabling technology into a national network. The NanoNed program was organised into eleven independent programs or flagships, among these also NanoPhotonics. In 2011 has been followed by NanoNextNL[57], a consortium of more than a hundred companies, nine knowledge intensive institutes, six academic medical centres and thirteen universities. Various stakeholders collaborate in fundamental as well as applied research in research projects. Relevant priority areas comprise functional nanophotonics and active nanophotonic devices. NanoNextNL is expected to grow into an open-innovation ecosystem, with new partners joining the consortium. Industry commits to continue its support to NanoNextNL after 2015. Complementary the IOP Photonics Devices - the national research program on Photonics – was launched in 2006 and will end in 2015. Photonics research will be further funded in the Dutch Topsectors, especially the Topsector High Tech Systems & Materials.
- In Spain, in the Sixth National Scientific Research, Development and Technological Innovation Plan (2008-2011), the Strategic Action for Nanoscience and Nanotechnology, New Materials and New Industrial Processes (SANSNT) addressed seven priorities including Materials for applications in electronics and photonics, especially organic materials.

  Within the new Spanish State Plan for Scientific and Technical Research and Innovation 2013-2016, endorsed in February 2013, different funding support instruments will be available for the Key Enabling Technologies development and dissemination, including nanotechnology, (e.g R+I+i projects, innovation and technology modernisation projects).
- The French Agence National de la Recherche (ANR) channels public funding into priority areas including Nanotechnologies & Manufacturing. The P2N programme[58] aims since 2006 at strengthening national excellence in the areas of micro and nano-engineering (ranging from core technologies to systems), and speed up technology transfer to French firms in order to exploit the extraordinary potential of the nanotechnologies. Nanophotonics is among the thematic

[55] FinNano, the Finnish nanoscience and nanotechnology programme, was established in 2005 and is coordinated jointly by Tekes and the Academy of Finland. Over EUR 120 million were invested by the programme between 2005 and 2010, with the aim of providing support across the whole innovation chain from basic research to commercial products. One priority area of the programme was the application of nanotechnology for Health and Well-being. More recently, Finland has moved away from specific funding of nanotechnology activity.

[56] https://www.ffg.at/nano-das-programm

[57] http://www.nanonextnl.nl/

[58] http://www.agence-nationale-recherche.fr/en/projects-and-results/calls-for-proposals-2013/aap-en/nanotechnologies-and-nanosystems-p2n-2013/

priorities that have been targeted in annual calls.

- Germany was the first country in Europe recognising a need for specific funding measure for nanotechnology and photonics, introducing the lead innovation programme "NanoLux" as early as 2001. The programme Optical Technologies (2002-2012, total funding of EUR 275.5 million administered by VDI Technologiezentrum) supported cooperative R&D projects in the realm of health-care systems and biotechnology, environment, traffic and mobility, nano-electronics, information and communication. Its successor, the Photonics Research programme has been launched in 2012 with a funding of EUR 100 million per year. It is subdivided into three fields of action: optical systems, especially next generation optical systems; innovative applications of light for humans, production and the environment; promotion of start-ups and creation of favourable general conditions.
- In addition, in Germany at regional level, the Research Strategy of Thuringia (2008) covered research areas such as photonics; optical technologies, micro and nano technologies, microelectronics; and information and communication technologies. The main fields of activity of regional research policy are (i) to support competitiveness, (ii) to strengthen networks, (iii) to support young researchers, and (iv) to invest in infrastructure.

Many of the Member State nanotechnology policies and programmes are identified in the table below. In addition to individual Member State initiatives, there are bilateral and multilateral collaborations between countries, agencies and research organisations. Most notable is the pooling of Member State resources and collaboration to address common issues as mentioned in the sections on European policies and programmes.

In addition to national policy on nanotechnology and manufacturing, national websites highlight its importance and some countries actively promote themselves as leaders in nanotechnology in areas including those relevant to photonics. For example:

- From France, the web site of Campus France[59] states:
  With more than 5,300 researchers and 240 laboratories working in the nanosciences and nanotechnologies, French institutions are engaged in a great many nano-research projects in the broad fields of electronics, communications, materials, energy, biotechnologies, pharmacology, medicine, health, and the environment. [….] With the research infrastructure built since the 1990s, France is one of the leaders in basic research in the nanosciences. The country ranks second in Europe, after Germany, in the amount invested in nanoscience research, and fifth in the world in number of publications in the field."

- On the German Trade and Invest Agency[60] website provides the information that: "Approximately half of the nanotechnology companies in Europe are from Germany; the country is number one in Europe in the nanotechnology industry. German companies manufacture products in the areas of nanomaterials, nanotools, nanoanalytics, and nanotools accessories (e.g. vacuum and cleanroom technology, plasma sources, etc.). They also manufacture and utilise nano-optimised components and systems, and they provide services in the areas of consulting, contract coating, technology transfer, and commissioned analysis and research.

59 http://ressources.campusfrance.org/catalogues_recherche/recherche/en/rech_nano_en.pdf
60 http://www.gtai.de/

Table 4-1: Member State policies and programmes for nanotechnology (including photonics)

Country	Name of Initiative	Dates	Relevance	Description	Target groups	Implementing body	Budget (EUR millions)
AT	Austrian NANO Initiative[61] (NANO)	2004-2011	Directly Targeting NT	Multiannual, funding collaborative R&D, co-ordinating NANO-related policy measures at national and regional levels.	IND SME HEI PRO	FFG	70 over 8 years
AT	------	From 2012	Thematic, not NT Specific	Since 2012, NT R&D is being supported via FFG's thematic research funding e.g. Production of the Future	All	FFG	450 for all disciplines (over the preceding 4 years when funding was managed by BMVIT)
DK	Strategic Research in Growth Technologies[62]	From 2005	Directly Targeting NT	Programme to strengthen research at the bio-nano-ICT interface for socio-economic benefit	IND SME HEI PRO	Innovation Fund Denmark	c. 10 per annum
FI	FinNano[63]	2005-2009	Directly Targeting NT	Multiannual funding for nano S&T to study, exploit and commercialise nano.	IND SME HEI PRO	Tekes	70 over 5 years
FR	PNANO P2N	2002-5 2006 -13	Directly Targeting NT	Nanophotonics is among the thematic priorities. R&D on • Nanotechnologies, Nanodevices, Micro-Nanosystems • Simulation and modelling of nanosystems • Nanotechnologies for biology, health and agro-food • Nanotechnologies for energy and environment • Integrative Research Projects for Nanosystems	IND SME HEI PRO and individuals	ANR[64]	139.8 for P2N over 8 years
DE	Nanotechnology Conquers Markets	2004-2006	Directly Targeting NT	Five leading-edge innovation programmes including NanoLux – optics.	All	BMBF	24 over 3 years
DE	Nano Initiative – Action Plan	2006-2010	Directly Targeting NT	Cross-departmental initiative led by BMBF: to speed up the use of the results of nanotechnological research for innovations; introduce nanotechnology to more sectors and companies; eliminate obstacles to innovation by means of early consultation in all policy areas; and (4) enable an intensive dialogue with the public.	All	BMBF	640 over 5 years
DE	Innovation Alliances	2007-2012	Directly Targeting NT	For strategic long-term co-operation between multiple industry and public research partners. Funds R&D, other innovation-related activities.	All	BMBF	500 over 6 years

[61] https://www.ffg.at/nano-aktuell ; https://www.ffg.at/11-ausschreibung-produktion-der-zukunft
[62] http://innovationsfonden.dk/en/about-ifd
[63] www.tekes.fi
[64] http://www.agence-nationale-recherche.fr/

Country	Name of Initiative	Dates	Relevance	Description	Target groups	Implementing body	Budget (EUR millions)
				Public and private funds are combined in a 1:5 ratio.			
NL	NanoNed	2004-2011	Directly Targeting NT	NanoNed was organised into eleven independent flagships based on regional R&D strength and industrial relevance, including NanoPhotonics.	IND SME HEI PRO and individuals	Dutch Ministry for the Economy	235 over 8 years
NL	NanoNextNL	2011-2015	Directly Targeting NT	Consortium-based system (over one hundred companies, nine knowledge intensive institutes, six academic medical centres and thirteen universities). Stakeholders collaborate on fundamental and applied research projects.	IND SME HEI PRO and individuals	Dutch Ministry for the Economy	125 over 5 years
ES	Strategic Action of Nano Science, Nano technologies, new materials and new industrial processes	2008-2011	Directly Targeting NT	To enhance the competitiveness of industry by generating new knowledge and applications based on the convergence of new technologies, where nanotechnology plays a central role.	IND SME HEI PRO	Ministry	33 over 4 years
UK	Micro and Nanotechnology Manufacturing Initiative[65]	2003-2007	Directly Targeting NT	Support for collaborative R&D and capital infrastructure, co-financed by industry	Industry	DTI	329 over 4 years, over 100 from public funds
UK	UK Nanotechnologies Strategy	2009-2012	Directly Targeting NT	Targets the ways by which nanotechnologies can address major challenges facing society such as environmental change, ageing and growing populations, and global means of communication and information sharing.	IND SME HEI PRO	TSB, EPSRC, BBSRC and MRC	
UK	Key Enabling Technologies Strategy	2012-2015	NT as underpinning technology	Addresses four enabling technologies - advanced materials; biosciences; electronics, sensors and photonics; and information and communication technology (ICT) to support business in developing high-value products and services in areas such as energy, food, healthcare, transport and the built environment. Nanotechnology is identified as having a significant underpinning role across most of these technology areas, particularly in the healthcare and life sciences sectors.	Business mainly	Innovate UK	GBP 20m a year in higher-risk, early-stage innovation across advanced materials; biosciences; electronics, sensors and photonics; and ICT

[65] http://www.innovateuk.org/

5 POLICIES AND PROGRAMMES IN OTHER COUNTRIES[66]

5.1 Europe

5.1.1 Non-EU Member States

5.1.1.1 Norway

From 2002 to 2011, Norway addressed nanotechnology (including photonics) through its Programme on Nanotechnology and New Materials (NANOMAT)[67]. In 2012, a follow-on programme to run until 2021 was initiated, the Nanotechnology and Advanced Materials Programme (NANO2021)[68]. Managed by the Research Council of Norway[69], this large-scale programme covers research on nanoscience, nanotechnology, micro-technology and advanced materials. The programme is designed to further raise the level internationally of the Norwegian knowledge base in nanotechnology and advanced materials. NANO2021 receives funding from the Ministry of Education and Research and the Ministry of Trade and Industry. The annual budget in the period 2013-2021 has been set at NOK 92.1 million (EUR 10 million at the current exchange rate, October 2015)[70].

Within thematic priority area three of NANO2021, the programme addresses nanoscience, nanotechnology, micro-technology and advanced materials. The last area is particularly relevant for photonics, since it includes materials with photovoltaic, thermal and optical properties[71].

5.1.1.2 The Russian Federation

The Russian Federation came comparatively late to nanotechnology as a topic for research, development and innovation policy. It was only in 2007 that a comprehensive government effort in the field began, with the launch in April of that year of a strategy for the development of the 'nano-industries'. The strategy was to be realised through a series of Federal Target Programmes, amongst which was one specifically dedicated to the development of nanotechnology and the creation of new government bodies for that purpose. The main focus of Russian nanotechnology efforts since that time has been on the development of a domestic infrastructure for nanotechnology research and development as well as for innovation, commercialisation and manufacturing of nano-products. This is expected to remain the major theme for the coming years.

State institutions have been the principal actors in the field of nanotechnology in Russia for the intervening period. The State corporation, RUSNANO, has had primary responsibility for the development of nanotechnology innovation and its commercialisation. RUSNANO was the outcome of a reorganisation in 2011 of the State "Russian Corporation of Nanotechnologies" that was established in 2007. It was set up as one of several state corporations intended to lead the economic modernisation that was proposed in the '*Concept for the Long-Term Socio-Economic Development of the Russian Federation'*.

RUSNANO now combines an open joint-stock company and a Fund for Infrastructure and Educational Programmes (FIEP). It had capital funding in 2008-2009 of over USD 4 billion (EUR 2.8 billion[72]) but this dropped to USD 2.6 billion (EUR 1.9 billion[73]) by the end of 2010, reducing further thereafter. A gradual privatisation of RUSNANO began in 2011. The mission of RUSNANO is to grow the national nanotechnology industry through the commercialisation of nanotechnology and the co-ordination of nanotechnology-related innovation. It acts as a co-investor in nanotechnology projects having substantial economic or social potential. RUSNANO has a very wide range of activities spanning from research to foresight to infrastructure, education, standards and certification. Its research projects fall under six clusters, some of them relevant to photonics such as the solar energy cluster and the optoelectronics cluster. As of October 2010, 15 out of 83 industrial investment projects were on

[66] The UN method of classifying countries by macro geographical (continental) regions and geographical sub-regions was followed (http://unstats.un.org/unsd/methods/m49/m49regin.htm)
[67]http://www.forskningsradet.no/prognett-nano2021/Artikkel/About_the_programme/1253970633592?lang=en
[68]http://www.forskningsradet.no/servlet/Satellite?c=Page&pagename=nano2021%2FHovedsidemal&cid=1253969916237&langvariant=en
[69] http://www.forskningsradet.no
[70] Nanotechnology and Advanced Materials – NANO2021: Work Programme
[71] Nanotechnology and Advanced Materials – NANO2021: Work Programme
[72] Average yearly conversion rate, 2008-2009 (*source*: www.wolframalpha.com)
[73] Average yearly conversion rate, 2010 (*source*: www.wolframalpha.com)

nano-photonics, as well as 32 on nanomaterials and 7 on nano-electronics[74].

5.1.1.3 Switzerland

Basic (fundamental) research is funded at national level through the Swiss National Science Foundation (SNF) and the Commission for Technology and Innovation (CTI) and takes place mainly in the Swiss Federal Institute of Technology (ETH) and the universities, as well as some 30 research organisations. Applied research and the transfer of research to market innovation takes place in industry and "Fachhochschulen" (Universities of Applied Research). Two-thirds of R&D investment (which in Switzerland is almost at the EU target of 3% of GDP) comes from private industry.

CTI funds the Swiss MNT network (micro and nanotechnology) as one of the core innovative themes of national and international importance[75]. The Swiss MNT Network is an R&D consortium of the major public R&D institutions in micro and nanotechnology whose goal is to simplify access to industries looking for competences and expertise for their projects[76]. Members include ETH Zürich, Hightech Zentrum Aargau, Centre of Micronanotechnology (EPFL), Adolphe Merkle Institute and companies such as IBM, BASF and Novartis. There are also some regional networks that include nanotechnology as priority: i-net innovation networks Switzerland – i-net Nano[77], and Nano-Cluster Bodensee[78]. Most activities are strongly focused on R&D to support industry.

5.2 The Americas

5.2.1 North America

5.2.1.1 Canada

One national initiative for photonics is the Canadian Photonics Fabrication Centre (CPFC)[79], which opened in 2005 as a partnership between the National Research Council and Carleton University. Its aim is to support the growth of the photonics sector in Canada. The Canadian government and the province of Ontario contributed CDN 30 million (EUR 45 million)[80]and CDN 13 million (EUR 19.5 million) respectively to the capital cost of the building and equipment. The CPFC was located at the NRC laboratories and the NRC covered the operating costs of the facility.

Nanotechnology is largely promoted in Canada mainly at the level of its Provinces, for example in Alberta and Quebec.

Alberta

The National Institute for Nanotechnology (NINT) is a research institution located in Edmonton on the main campus of the University of Alberta. Its primary purpose is nanotechnology research. The institute was established in 2001 as a partnership between the National Research Council of Canada (NRC), the University of Alberta and the Government of Alberta. As an institute of the NRC, its core funding comes from the Government of Canada and additional funding and research support from the university, the Government of Alberta and various federal and provincial funding agencies.

Following the announcement in 2007 of the Government of Alberta's Nanotechnology Strategy, nanoAlberta was created as an implementation organisation for that Strategy. NanoAlberta provides leadership to and co-ordination of the Province's wide range of capabilities, organisations and individuals with the aim of gaining a return of CND 20 billion (EUR 13.4 billion[81]) in market share for nano-enabled commerce by 2020.

Quebec

NanoQuébec is a not-for-profit organisation funded by the MEIE (Ministère de l'Économie, de l'Innovation et des Exportations du Québec). Its mission is to strengthen nanotechnology innovation, increase its diffusion and raise both capabilities and capacities in the Province in order that Quebec

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[74] Anatoly Chubais, RUSNANO Chief Executive Officer, "RUSNANO: fostering Innovations in Russia through Nanotechnology", USRBC 18th Annual Meeting, October 2010, San Francisco, California, USA, https://www.usrbc.org/pics/File/AM/2010/Presentations/Chubais_GB_830.ppt.pptx

[75] https://www.kti.admin.ch/kti/en/home/unsere-foerderangebote/Unternehmen/internationale-netzwerke-und-forschungskooperationen-neu/spezialthema-japan-schweiz1/foerderlandschaft-schweiz.html

[76] http://www.swissmntnetwork.ch/content/

[77] http://www.i-net.ch/nano/

[78] http://www.ncb.ch/wordpress_neu/

[79] http://www.nrc-cnrc.gc.ca/eng/solutions/facilities/prototyping_index.html

[80] Average rate 2005, CDN 1.5 to EUR 1.00 (www.x-rates.com)

[81] Current conversion rates, October 2015

becomes a centre of excellence for nanotechnology. The overarching and long-term aim is that of maximising economic impacts from nanotechnology in Quebec. Since December 2014, following a merger with the Consortium Innovation Polymères, NanoQuébec has formed part of Prima Québec, Quebec's advanced materials research and innovation hub.

Quebec's Nano Action Plan 2013-2018[82] specifically targets four priority sectors: microsystems, health, industrial materials and forestry. It covers infrastructure, financing of innovation, knowledge transfer and technology transfer, and national and international outreach horizontally across the four priority areas.

Via a central point, QNI or Quebec Nanotechnology Infrastructure, it co-ordinates and provides infrastructure for 300 experts using a fund of CND 300 million (EUR 200 million[83]). QNI has particular strengths in micro-nanofabrication, characterisation, synthesis and modelling. Other infrastructure can be accessed, but is not funded, through QNI.

The Action Plan has also led to the financing of technological feasibility projects (maximum 6 months); collaborative industry/university research projects (1 to 2 years); and international research projects with strategic NanoQuébec partners. Knowledge and technology transfer are supported through training, industry internships, and dissemination and awareness activities; by establishing networks and by organising interactive visits by experts. Outreach actions aim to attract new projects and finance to Quebec and to increase the engagement in international projects by people from Quebec.

5.2.1.2 The United States of America (US)

The National Nanotechnology Initiative[84] was launched in 2000 across a group of eight Federal agencies with some responsibility for nanotechnology research, application and/or regulatory activity and has grown to include 25 Federal agencies. It aims to create collaborations and bring together expertise to work on shared goals, priorities, and strategies thereby leveraging the resources of the participating agencies. The goals of the NNI Goals are to advance world-class nanotechnology research and development; foster the transfer of new technologies into products for commercial and public benefit; develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology; and support the responsible development of nanotechnology.

The NNI is managed within the framework of the National Science and Technology Council (NSTC), a Cabinet-level council under the Office of Science and Technology Policy at the White House. The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the NSTC facilitates planning, budgeting, programme implementation, and review across the NNI agencies. The National Nanotechnology Coordination Office (NNCO) was established in 2001 to provide technical and administrative support to the NSET Subcommittee, serve as a central point of contact for Federal nanotechnology R&D activities, and perform public outreach on behalf of the National Nanotechnology Initiative.

The NSET Subcommittee is composed of representatives from agencies participating in the NNI and NSET has Working Groups on Global Issues in Nanotechnology; Nanotechnology Environmental & Health Implications; Nano-manufacturing, Industry Liaison, & Innovation; and Nanotechnology Public Engagement & Communications. As can be seen from the above listing, photonics occurs under manufacturing, amongst other topics.

In February 2014, the National Nanotechnology Initiative released a Strategic Plan[85] outlining updated goals and five "programme component areas" (PCAs). The goals focus on extending the boundaries of research; fostering the transfer of technology into products; developing and sustaining skilled people (with the right infrastructure and toolset) for nanotechnology; and supporting responsible development of nanotechnology. The five PCAs include a set of five Nanotechnology Signature Initiatives (NSIs) as well as PCAs for foundational research; nanotechnology-enabled applications, devices, and systems; research infrastructure and instrumentation; and environment, health, and safety (all of which have relevance for photonics and nanotechnology). The five Nanotechnology Signature Initiatives (NSIs) are also highly-relevant to photonics covering:

- nanoelectronics for 2020 and beyond (including the area of merging nanophotonics with

[82] http://www.nanoquebec.ca/media/plan-action_en1.pdf
[83] Current conversion rates, October 2015
[84] http://www.nano.gov/
[85] http://www.nano.gov/sites/default/files/pub_resource/2014_nni_strategic_plan.pdf

nanoelectronics);
- nanotechnology for solar energy collection and conversion (that includes improving photovoltaic solar electricity generation);
- sustainable nanomanufacturing (targeting 3 classes of materials including optical metamaterials);
- nanotechnology knowledge infrastructure (NKI); and
- nanotechnology for sensors and sensors for nanotechnology.

The 2014 NNI Strategic plan also identifies the different priorities and interests of agencies, for example, the US Department of Agriculture (USDA) research on cellulosic nanocrystals that can be manipulated to produce photonic structures.

The NNI's budget supplement proposed by the Obama administration for Fiscal Year 2015 provides for USD 1.5 million (EUR 1.2 million[86]) of funding. Cumulative NNI investment since fiscal year 2001, including the 2015 request, totals almost USD 21 million (EUR 17 million[87]). Cumulative investments in nanotechnology-related environmental, health, and safety research since 2005 is nearly USD 900 million (EUR 680 million[88]). The Federal agencies with the largest investments are the National Institutes of Health (NIH), the National Science Foundation (NSF), the Department of Energy, the Department of Defence, and the National Institute of Standards and Technology (NIST).

Some of the above-mentioned institutions, like NIST, have areas dedicated to nanoscience and nanotechnology, but they do not have a specific photonics-sector focus. For instance, a fundamental part of NIST's mission is related to measurement sciences and standards development. However, NIST has subject areas that are linked to the photonics sector, such as nano-electronics and nanoscale electronics, nanofabrication, nano-manufacturing, and nano-processing, and nanostructured materials. NIST provides facilities to support production, through the Centre for Nanoscale Science and Technology (CNST)[89], established in 2007. The CNST facilitates the access to commercial state-of-the-art nanoscale measurement and fabrication tools through its NanoFab.

Another important actor active in nanotechnology is the National Science Foundation (NSF). This federal agency, with an annual budget of USD 7.3 million (EUR 6.8 million[90]) (FY 2015), funds approximately 24% of all federally supported basic research conducted by America's colleges and universities[91].

With particular reference to the photonics sector, the Directorate for Engineering, Division of Electrical, Communications and Cyber Systems (ECCS) at the NSF has a programme on Electronics, Photonics and Magnetic Devices (EPMD). The dedicated Optics & Photonics component of EPMD focuses on "research and engineering efforts leading to significant advances in novel optical sources and photodetectors, optical communication devices, photonic integrated circuits, single-photon quantum devices and nano-photonics"[92]. Other connected areas are novel optical imaging and sensing applications and solar cell photovoltaics.

As for NSF, the US Department of Energy (DoE) considers nanoscience and nanotechnology in the field of photonics as crucial areas. The Centre for Nanoscale Materials, a partnership between the DOE and the State of Illinois, is one of offices of the DoE[93] with the main goal of conducting basic research. Among its research areas is nano-photonics (e.g. hybrid optical states in coupled nanoparticle systems, energy dissipation and transduction in nanostructures, understanding light harvesting and charge separation in nanoscale systems) including current work on the development of "important new approaches to fabricate, characterise, and manipulate nanoparticle hybrid structures with controllable optical properties. This will produce important technology and device opportunities, such as photo-induced catalytic processes, novel ultrafast optical switching mechanisms, and energy conversion processes"[94].

The US Department of Defence contributes as well to the progress of nanotechnology and photonics.

[86] Average yearly conversion rate, 2015 (*source*: www.wolframalpha.com)
[87] Average yearly conversion rate, 2001-2015 (*source*: www.wolframalpha.com)
[88] Average yearly conversion rate, 2005-2015 (*source*: www.wolframalpha.com)
[89] http://www.nist.gov/cnst/index.cfm
[90] Current conversion rate, November 2015 (*source*: www.wolframalpha.com)
[91] http://www.nsf.gov/about/
[92] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13379&org=ECCS&from=home
[93] http://www.anl.gov/cnm/about-us
[94] http://www.anl.gov/cnm/group/nanophotonics

In July 2015, the Integrated Photonics Institute for Manufacturing Innovation[95] was launched to develop lower-cost, higher-speed, and more efficient manufacturing processes for photonic circuits, by: (i) developing an end-to-end photonics 'ecosystem' in the US; (ii) creating a standardised platform; (iii) assembling a world-class team of organisations from across the photonics industry; (iv) pairing photonics companies and top research universities. The Institute was created with a total investment of over USD 610 million (EUR 555 million[96]), USD 110 million (EUR 110 million[97]) in Federal funds, and more than USD 500 million (EUR 455 million[98]) in non-Federal contributions, as the sixth of nine public-private partnerships (the National Network of Manufacturing Institutes (NNMI)) established to boost advanced manufacturing. The award of funding for the Institute was made to a consortium of 124 companies, non-profit organisations, and universities led by the Research Foundation of the State University of New York (RF SUNY).

In additional to these Federal initiatives, there are several policy initiatives at US State level[99]. Programmes for the promotion of nanotechnologies currently exist in 23 states. Notable examples are the Texas Emerging Technology Fund[100], the Oklahoma Nanotechnology Initiative[101], the Illinois Nanotechnology "Collaboratory"[102], and the Oregon Nanoscience and Microtechnologies Institute (ONAMI)[103]. The State-level organisations typically undertake some or all of the following activities: fostering collaboration on nanotechnology topics and challenges between researchers and research centres; higher education/industry joint projects; education and outreach; access to technology experts and infrastructure; early-stage funding and investment opportunities; technology transfer and commercialisation; and awareness raising in the community.

5.2.2 South America

5.2.2.1 Argentina

A first initiative to foster nanotechnology in Argentina was established in 2003 when the national Science and Technology Secretariat started to organise research networks in the field. In 2004, the Secretariat, looking to address gaps in what being done under the National Agency for Scientific and Technological Promotion (ANPCYT, Agencia Nacional de Promoción Científica y Tecnológica[104]) as a result of which four nanoscience and nanotechnology networks were approved in 2005, bringing together around 250 scientists. In the same year, the Argentinian-Brazilian Nanoscience and Nanotechnology Centre (CABN, Centro Argentino-Brasileno de Nanociencia y Nanotecnología) was created as a binational co-ordination body integrating research groups, networks of nanoscience and nanotechnology, and companies in Argentina and Brazil, in order to support scientific and technological research in the area and to improve the human and scientific resources of both countries.

The Argentinian Foundation for Nanotechnology (FAN)[105] was initiated also in 2005 by the Economy and Production Ministry, with the aim of stimulating training and developing technical infrastructure to promote advances in nanotechnology and the adoption of nanotechnology by industry. It also aimed to encourage the participation of researchers, institutions and companies from Argentina in international networks.

While previous national programmes had differentiated between funding for the public sector on the one hand (essentially the research networks) and the private sector on the other (projects of the FAN), the nano sectorial funds (FS-NANO) launched in 2010 provided funding to projects dedicated to basic and applied science via public-private partnerships.

In 2011, the Ministry of Science, Technology and Productive Innovation issues published the Argentina Innovadora 2020 (Innovative Argentina Plan 2020): National Plan of Science, Technology and Innovation. The plan is focused on three general-purpose technologies (nanotechnology,

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[95] https://www.whitehouse.gov/the-press-office/2015/07/27/fact-sheet-vice-president-biden-announces-new-integrated-photonics
[96] Current conversion rate, July 2015 (*source*: www.wolframalpha.com)
[97] Current conversion rate, July 2015 (*source*: www.wolframalpha.com)
[98] Current conversion rate, July 2015 (*source*: www.wolframalpha.com)
[99] http://www.nano.gov/initiatives/commercial/state-local
[100] http://gov.texas.gov/. As of October 2010, the Texas Emerging Technology Fund has given a total of UDS 173 million to 120 companies as well as UDS 161 million to educational institutions.
[101] http://www.oknano.com /
[102] http://nano.illinois.edu/collaboration/index.html
[103] http://onami.us/
[104] http://www.agencia.mincyt.gob.ar/frontend/agencia/fondo/agencia
[105] http://www.fan.org.ar/en/

biotechnology and information and communication technology (ICT)). The plan addresses six strategic sectors, including energy and industry, both relevant for the photonics sector. For instance, the former contains actions on interconnection of photovoltaics system to the urban electricity network and development of a solar thermoelectric park [106].

5.2.2.2 Brazil

Systematic policy support for nanotechnology started in 2001, when the Brazilian Ministry of Science and Technology (MCT) through the Brazilian National Research Funding Agency (Conselho Nacional de Desenvolvimento Científico e Tecnológico or "CNPq") earmarked BRL 3 million (USD 1 million) (EUR 1.12 million[107]) over four years to form Co-operative Networks of Basic and Applied Research on Nanosciences and Nanotechnologies. Four national research networks were established: molecular nanotechnologies and interfaces; nano-devices; semiconductors and nanostructured materials; and nano-biotechnology. In late 2004, a network on Nanotechnology, Society and Environment was created independent of the formal funding mechanisms.

Since 1999, Brazil's national plan has comprised an annual budget and a four-year strategic plan (the Plano Plurianual or PPA). In 2003, the Ministry created a special division for the general co-ordination of nanotechnology policies and programmes whose work resulted in a proposal for specific nanotechnology-related funding. That proposal was taken up in the PPA in 2004-2007 which provided for BRL 78 million (c. USD 28 million) (EUR 22 million[108]) over 4 years for the Programme for the Development of Nanoscience and Nanotechnology. The aim of the programme was "to develop new products and processes in nanotechnology with a view to increasing the competitiveness of Brazilian industry" which it implemented by supporting networks, research laboratories and projects.

A review of the funding in the light of the 2004 Industrial, Technological and Foreign Trade Policy, the government reconsidered the original budget and increased Federal investment for 2005 and 2006 from the original USD 19 million (EUR 15 million[109]) for those two years to c. USD 30 million (EUR 24 million[110]). Ten new research networks were set up to continue previous research activities but linking more closely to broader industry, technology, and trade policies. Industrial policy helped to reinforce the strategic status attributed at national level to nanotechnology and its role in enhancing Brazil's competitiveness. Of particular important in the programmes were the development of qualified human resources, the modernisation of infrastructure and the promotion of university-industry co-operation.

In 2012, the Brazilian Ministry for Science, Technology and Innovation (MCTI) launched the SisNANO[111] initiative, enabling scientists throughout Brazil to conduct experiments at 26 "open" laboratories offering the very best equipment for research in nanotechnology. University students and staff can use the facilities free of charge – provided they submit a good research proposal – while scientists working in industry are able to access specialist equipment and expertise at highly subsidised rates. An example of laboratory relevant for the photonics sector is the Centre of Nanotechnology for Materials and Catalysis (CENANO). Among the strategic sectors identified in the nanotechnology area, the energy one is linked to photonics.

In 2013, MCTI launched the Brazilian Nanotechnology Initiative (IBN) with funding estimated to be BRL 440 million (EUR 148 million[112]) for the 2013-2014 period. The implementation of IBN was an effort to further strengthen nanotechnology in Brazil by strengthening academic and industry linkages thereby to promote the scientific and technological development of the nanotechnology sector.

5.3 Asia

5.3.1 Eastern Asia

5.3.1.1 China

The transition of China from a centrally planned to a more market-oriented economy, begun in the 1980s, has also led to greater decentralisation of the science and technology (S&T) system. Central

[106] http://www.argentinainnovadora2020.mincyt.gob.ar/?page_id=194
[107] Average yearly conversion rate, 2001 (*source*: www.wolframalpha.com)
[108] Average yearly conversion rate, 2004-2007 (*source*: www.wolframalpha.com)
[109] Average yearly conversion rate, 2005-2006 (*source*: www.wolframalpha.com)
[110] Average yearly conversion rate, 2005-2006 (*source*: www.wolframalpha.com)
[111] Sistema Nacional de Laboratórios em Nanotecnologias ftp://ftp.mct.gov.br/Biblioteca/39717-SisNANO.pdf
[112] Average yearly conversion rate, 2013-2014 (*source*: www.wolframalpha.com)

government is increasingly co-ordinated S&T, rather than managing research and development (R&D) with research institutions taking on a greater role in policy, setting their own research agendas in the context of the national Five-year Plans.

The National High Technology Research and Development Programme (the 863[113] programme announced in 1986) focuses on key high technology fields of relevance to China's national development, supporting research and development, strengthening technological expertise and laying the foundations for the development and growth of high technology industries. Its goals are 'promoting the development of key novel materials and advanced manufacturing technologies for raising industry competitiveness' including nanomaterials. The programme is supervised by the National Steering Group of S&T and Education, and is managed by the Ministry of Science and Technology.

The 863 Programme is implemented through successive Five-Year Plans. In addition to nanotechnology research funding, the Tenth Five-Year Plan (2001-2005) targeted commercialisation and development of nanotechnology. The Government disaggregated nanotechnology development between short-term projects (development of nanomaterials), medium-term projects (development of bio-nanotechnology and nano medical technology), and long-term projects (development of nano electronics and nanochips). The Eleventh Five-Year Plan (2007-2012) thereafter emphasised innovative technologies, including the development of new materials for information technology, biological and aerospace industries, and commercialising of the technology for 90-nanometre and smaller integrated circuits.

The 1997 "National Plan on Key Basic Research and Development" together with the "National Programme on Key Basic Research Project (973 Programme)" sought to strengthen basic research in line with national strategic targets[114]. The 973 Programme complements the 863 programme, funding basic research on nanomaterials and nanostructures (i.e. carbon nanotubes). The National Steering Committee for Nanoscience and Nanotechnology (NSCNN) was established in 2000 to coordinate and streamline all national research activities including overseeing the 863 and 973 programmes. The NSCNN consists of the Ministry of Science and Technology (MOST), the Chinese Academy of Sciences (CAS), the National Natural Science Foundation (NSFC), the National Development and Reform Commission (NDRC), the Ministry of Education (MOE) and the Chinese Academy of Engineering (CAE).

The Medium-and Long-term National Plan for Science and Technology Development 2006-2020 (MLP) aims to achieve the promotion of S&T development in selected key fields and to enhance innovation capacity. The MLP calls for more than 2.5% of GDP to be invested in R&D, for S&T to contribute at least 60% to economic growth, for dependence on foreign technologies to decrease to under 30%, and for China to rank in the top five in the world for patents and citations in international publications.

Nanotechnology is given priority status under the MLP, being seen as one of the Chinese 'megaprojects' in science. Four major scientific research programmes are foreseen, one on quantum regulations studies (related to artificial photonic crystal and photonic materials). As the MLP is implemented in the context of the Five-Year Plan for S&T Development (2011-2015), it is important that it also emphasises key technologies for strategic and emerging industries (including nanotechnology with photonics, ICT, manufacturing and agriculture).

In addition, China is promoting itself in nanotechnology. From http://www.china.org.cn/: "China is positioning itself to become a world leader in nanotechnology … Nanotechnology has many potential applications with significant economic consequences in energy, defence, food, industrial design, agriculture, medicine, etc. …. Today, China leads the world in the number of nanotechnology patents".

5.3.1.2 Japan

Strategic prioritisation of nanotechnology started in Japan under the Second Science and Technology Basic Plan (STBP) 2001-2005. One of eight priority R&D topics of national important, nanotechnology and materials were identified alongside ICT, energy, environmental sciences, manufacturing technology and life sciences together with the cross-cutting areas of infrastructure and frontier research. Nanotechnology was seen as being relevant to a broad range of fields and it was expected to help Japan to maintain its technological edge. Total governmental funding of this field grew in

[113] The programme is named for its date, the 86 for 1986 and the 3 for the third month, hence 86/3 or 863. Likewise for the 973 programme launched in 1997.

[114] http://www.chinaembassy.bg/eng/dtxw/t202503.htm

these years from JPY 85 billion (EUR 782 million)[115] in 2001 to JPY 97 billion (EUR 709 million[116]) in 2005.

In the subsequent STBP[117] which ran from 2006 to 2010, Japan established nanotechnology and materials as one of its four priority research fields, the others being environmental sciences; information and communications, and life sciences. Together with energy, environment, manufacturing and frontiers, these formed eight Promotion Areas. The total budget over the five years was JPY 250 trillion (EUR 200 billion)[118].

There were five sub-areas under nanotechnology and materials –nano-electronics; fundamentals for nanotechnology and materials; materials; nanotechnology and materials science; and nano-biotechnology and biomedical materials.

In 2010, a New Growth Strategy was introduced to combat the lengthy stagnation in the Japanese economy. The strategy sought to create jobs by tackling the issues faced by the economy and society. This took the form of a reorientation of priorities towards green innovation (reducing emissions and addressing climate issues), life innovation (healthy and long living, making japan a health superpower), the Asian economy (issues of specific Asian concern including falling birth rates and ageing societies) and tourism and the regions. Growth-related strategies for ('making Japan a superpower in') science, technology and ICT, for employment and human resources, and for the financial sector were also identified as essential in supporting growth. The strategy also addressed the issues arising from the earthquake, tsunami and nuclear crisis of 2011.

These same issues were incorporated in 2011 into the Fourth Science and Technology Basic Plan (2011-2015) with a budget of EUR 250 billion (JPY 25 trillion). As with the New Growth Strategy, and in contrast to the previous Basic Plan for Science and Technology, the Fourth Basic Plan shifted away from emphasising technologies towards "demand driven and solution-oriented topics" as well as to "problem solving and issue-driven policies" and the "deepening the relationship between society and science and technology." Two broad based areas are prioritised: Life Innovation and Green Innovation and an emphasis has been placed on technologies to reduce global warming, provision and storage of energy supply, renewable energies, and diffusion of such technologies. As there is no specific emphasis on individual technologies, nanotechnology is incorporated across research and development without being specifically targeted.

In the specific field of nano-photonics, the Nano-photonics Research Centre (NPC) is pursuing University-Industry Collaborations in nano-photonics and is active in international projects[119].

5.3.1.3 Korea (South)

With specific reference to nano-photonics, the Korean Institute of Science and Technology (KIST)[120] has a Nano-photonics Research Centre in its Material and Life Science Division. The centre focuses on optic devices, solar cells, fibre optic devices and memory devices, using various nano structures such as quantum dot, quantum well, nano wire, and photonic crystals[121].

Support for nanoscience and nanotechnology in Korea reached a new level in December 2000 with the announcement by the National Science and Technology Council (NSTC)[122] of the Korean National Nanotechnology Initiative (KNNI). Nanotechnology was also identified as one of six priority fields in the National Science and Technology Basic Plan (2002–2006). The NT Development Plan was approved by the NSTC on in July 2001 and the NT Development Promotion Act passed in November 2002 by the National Assembly. The initiative is now in its 3rd phase (2011-2020), with focus on

[115] Average yearly conversion rate, 2001 (*source:* www.europarl.europa.eu/RegData/etudes/note/join/2007/379231/IPOLTRAN_NT%282007%29379231_EN.pdf)

[116] Average yearly conversion rate, 2005 (*source:* www.europarl.europa.eu/RegData/etudes/note/join/2007/379231/IPOL-TRAN_NT%282007%29379231_EN.pdf)

[117] https://www.jsps.go.jp/english/e-quart/17/jsps17.pdf

[118] Average yearly conversion rate, 2006 (*source:* www.europarl.europa.eu/RegData/etudes/note/join/2007/379231/IPOLTRAN_NT%282007%29379231_EN.pdf)

[119] http://www.npc.t.u-tokyo.ac.jp/index_e.html

[120] KIST is a science and technology institute. It was the first S&T research institute founded in Korea following the joint statement by the Presidents of Korea and the US on the "Establishment of a Korean Industrial and Applied Science R&D Institute" (1966) http://eng.kist.re.kr/kist_eng/?sub_num=728

[121] http://eng.kist.re.kr/kist_eng/?sub_num=728

[122] http://www.nstc.go.kr/eng/

clean nanotech. Investment in phase 1 (2001-2005) was 105.2 billion Won (EUR 83 million[123]); phase 2, 277.2 billion Won (EUR 1,541.8 million[124]).

Under its KNNI, Korea has focused on establishing specific support mechanisms (programmes, systems and societies) and centres of excellence across the country. The launching of the National Programme for Tera-Level Nanodevices (2000) was followed by the founding of the Nanotechnology Industrialisation Support Centre (2001) and the Korean Advanced Nanofabrication Centre[125] (KANC) (2003). In more recent times, building on former centres, Korea established two NST centres at the Institute for Basic Science, the Centre for Nanoparticle Research and the Centre for Nanomaterials and Chemical Reactions (2012)[126]. In total, 24 nanotechnology-related centres now exist in Korea. In addition, by 2010 over forty universities had nanotechnology departments.

Under the Nanotechnology Development Promotion Act 2002, Korea also established in 2004 the Korean Nano Technology Research Society (KoNTRS)[127] as a mechanism for co-operation between researchers working on nanotechnology throughout the country, to develop collaborative research programmes between institutions (public and private) and to support the government in establishing sound national NST policies.

Korea has continued to invest in nanotechnology, with the review by NSTC in 2006 of the first five years of its NNI leading to support continuing for an additional ten years. In this third phase of the NT Development Plan (2011-2020) there is more focus on clean nanotechnology and overall the policy has evolved, moving away from funding fundamental research towards more application-driven actions.[128]

Korea has also sought to develop its nanotechnology policy and policy system, with the production of the Korean Nanotechnology Roadmap in 2008 and the establishment of the National Nanotechnology Policy Centre (NNPC) in 2010. The NNPC announces on its web site[129] the national vision for Korea to be "the world's number one nanotechnology power" and the four goals:

- "To become a leading nation in nanotechnology with systematic nanotechnology R&D programmes;
- To create a new industry based on nanotechnology;
- To enhance social and moral responsibility in researching and developing nanotechnology; and
- To cultivate advanced nanotechnology experts and maximise the utilisation of nanotechnology infrastructure."

Mid-term and long-term strategies for nanotechnology in Korea which have been developed and implemented since about 2009 include:

- The Fundamental Nanotechnology Mid-term Strategy [NT 7-4-3 Initiative] through which the Ministry of Education, Science and Technology (MEST) supported 35 green nanotechnologies in seven areas as well as funding four infrastructure projects;
- The Nano Fusion Industry Development Strategy by MEST and the then Ministry of the Knowledge Economy (MKE) which sought to support nanotechnology all across the value chain, from the research laboratory to the marketplace;
- The National Nano Infrastructure Revitalisation Plan, also by MEST and MKE, to link nanotechnology infrastructures together thereby giving them new impetus; and
- The Nano Safety Management Master Plan 2012-2016 to define methods and processes for the identification and manage any safety risks that emerge with the development, commercialisation and manufacture of nanotechnology products.

2012 saw the creation of the Nano-Convergence Foundation (NCF)[130] whose remit is to increase the commercialisation of national NST research outcomes. It operates jointly under the joint support of the Ministry of Science, ICT & Future Planning (MSIP) and the Ministry of Trade, Industry & Energy

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[123] Average yearly conversion rate, 2001-2005 (*source*: www.ecb.europa.eu/stats/exchange/eurofxref/html/eurofxref-graph-krw.en.html)
[124] Average yearly conversion rate, 2006-2010 (*source*: www.ecb.europa.eu/stats/exchange/eurofxref/html/eurofxref-graph-krw.en.html)
[125] http://www.kanc.re.kr/kancEnglish/center/center_overview.jsp
[126] https://www.ibs.re.kr/eng/sub02_04_03.do
[127] http://kontrs.or.kr/english/index.asp
[128] http://www.nanotechmag.com/nanotechnology-in-south-korea/
[129] http://www.nnpc.re.kr/htmlpage/15/view
[130] http://www.nanotech2020.org/download/english_brochure.pdf

(MOTIE). Korea plans to invest 930 billion Korean Won (ca. USD 815 million) (EUR 740 million[131]) by 2020 in the NST, with projects in the Nano Convergence 2020 programme eligible to receive up to 2 billion Korean Won (EUR 1.5 million[132]) each.

5.3.1.4 Taiwan (Chinese Taipei)[133]

The National Nanoscience and Nanotechnology Programme[134] was approved for a period of six years by the National Science Council (NSC) in 2002. With a budget envelope of USD 700 million (EUR 740 million[135]) and actual expenditure estimated to be USD 625 million (EUR 486 million[136]) over 2003-2008, the aim of the programme was to foster nanotechnology research and development in research institutes, universities and private companies, achieving academic excellence and supporting commercialisation. The Academic Excellence part of the programme includes physical, chemical and biological properties of nanostructures, nano-sensors (nano-probes), nano-devices and nano-biotechnology. Industrial applications are the remit of the Industrial Technology Research Institute (ITRI). ITRI has 13 research laboratories and centres in areas including optoelectronics, electronics, applied materials, biomedicine, chemistry and mechanics, many of which include photonics and others which use photonics in applications.

The National Nanoscience and Nanotechnology Programme also co-ordinates the nanotechnology research efforts of government agencies mainly through the establishment of common core facilities and education programmes, by promoting technology transfer and commercialisation into industrial applications and establishing international competitive nanotechnology platforms. Among the thematic priorities of the programme overall have been the design and fabrication of interconnects, interfaces and system of functional nano-devices, the development of MEMS/NEMS technology, and nano-biotechnology.

Taiwan’s Nanotechnology Community (NTC) was established in 2003 to identify commercial applications of nanotechnology and, in 2004, the Taiwan Nanotechnology Industrialisation Promotion Association (TANIPA) was set up by the Industrial Development Bureau at the Ministry of Economic Affairs (MOEA), with a strategic remit related to industrial applications of nanotechnology and to facilitate public-private co-operation.

Phase I of the National Nanoscience and Nanotechnology Programme was completed in 2008. Phase II was approved by the NSC in April 2008 to run for another six years (2009-2014) with the goal of strengthening and concentrating public resources on “Nanotechnology Industrialisation” i.e. the development of nanotechnology for domestic industry relevant to Taiwan and its growth into high-tech industry. Building on Phase I, the Phase II has supported nano-optoelectronics, nano-electrics, energy and environmental nanotechnology, nano-instrumentation, nano-materials and nano-biotechnology (all of which again can either cover photonics are a research area or use photonics in applications) and applied nanotechnology in traditional industries.

5.3.2 Southern Asia

5.3.2.1 India[137]

The Nanomaterials Science and Technology Initiative (NSTI) was launched by the Ministry of Science and Technology’s (MST) Department of Science and Technology (DST) in October 2001 to support priority areas of research in nanoscience and nanotechnology, strengthen national characterisation and infrastructural facilities, enhance nanotechnology education in order to generate trained manpower in the area, and create an applications-related interface between educational institutions and industry. The Indian government committed to investing USD 16 million (EUR 14 million[138]) in nanomaterials research and commercial development over the five-year duration of the initiative, 2002-2006. The funding was used for projects, centres of excellence, conferences and advanced

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[131] Current exchange rate, November 2015 (*source*: www.wolframalpha.com)
[132] Current exchange rate (November 2015) (*source*: www.ecb.europa.eu/stats/exchange/eurofxref/html/eurofxref-graph-krw.en.html)
[133] http://www.twnpnt.org/
[134] http://www.twnpnt.org/english/g01_int.asp
[135] Average yearly conversion rate, 2002 (*source*: www.wolframalpha.com)
[136] http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2768287/
[137] http://www.oecd.org/science/nanosafety/37277620.pdf; http://nanomission.gov.in/; http://www.ris.org.in/images/RIS_images/pdf/DP%20193%20Amit%20Kumar.pdf, http://erawatch.jrc.ec.europa.eu/erawatch/opencms/information/country_pages/in/country?section=ResearchPolicy&subsection=ResPolFocus
[138] Average yearly conversion rate, 2002-2006 (*source*: www.wolframalpha.com)

courses (schools), and post-doctoral fellowships[139].

A capacity-building programme ('mission') for nanoscience and nanotechnology (called Nano Mission)[140] was announced in 2007. It was implemented by DST with a budget of EUR 155 million over 5 years. In that time, India raised its publication output in nano S&T generating about 5000 research papers and about 900 Ph.Ds directly from Nano Mission funding. Under the programme, scientists were given access global state-of-the-art facilities in countries including Japan and Germany. Nano Mission has also facilitated discussions on standards for nanotechnology at national level.

The continuation of the Nano Mission was approved by the Government in February of 2014 and EUR 91 million (INR 650 crore) were sanctioned for the time period 2012 to 2017[141]. The programme will continue to support nanoscience and technology by promoting basic research, human resource development, research infrastructure development, international collaborations, national dialogues and nano-applications and technology development. In the area of development of products and processes, the programme has and will continue to focus on areas of national relevance including safe drinking water, materials development, sensors development, and drug delivery.

In addition to DST, several other agencies support nanotechnology research and development:

- The Council of Scientific and Industrial Research (CSIR)[142] has a network of 38 laboratories and other partners involving about 4600 scientists in research and development across a wide range of disciplines including nanotechnology and for application areas including electronics and instrumentations (photonics and optoelectronics are considered 'thrust areas').
- In 2003, the CSIR launched the New Millennium Indian Technology Leadership Initiative (NMITLI) to foster public-private partnerships via grant-in-aid funding to public partners and soft loans to their industrial partners. The initiative specifically targeted nanotechnologies; energy and materials.[143]
- The CSIR's International Science and Technology Directorate (ISAD) facilitates nanotechnology workshops and projects in collaboration with partners from South Africa, France, South Korea, China and Japan[144].
- The MST's Science and Engineering Research Council (SERC)[145] supports frontier and interdisciplinary research. Support for nanotechnology projects has been provided through its R&D schemes for basic science and engineering science.

5.3.2.2 Iran[146]

The Islamic Republic of Iran ranked 23rd in the world in nanotechnology in 2007, the highest-ranked Islamic country by citations and second to Korea in Asia[147].By 2012, it had moved to 10th place in the rankings[148, 149]. In 2013, Iran ranked 20th in science production in the world (Thomson Reuters). According to the Ministry, its share of global science production rose from 1.39% in 2013 to 1.69% in 2014, as measured by indicators including the number of scientific papers, the quality and quantity of documents, patenting inventions, industrial plans, partnership with foreign universities, and the use of technology in domestic organisations.

There are nine scientific committees responsible for organising and coordinating science activities including committees for nanotechnology, information technology, renewable energies, aerospace, environment, and biotechnology.

Iran started its activities with a Study Committee for Nanotechnology in 2001. Its work led to the development of the Iran Nanotechnology Initiative Council (INIC)[150], established in 2003 to develop policies to foster nanotechnology in Iran and monitors their implementation. The Council also funds

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139 http://www.oecd.org/science/nanosafety/37277620.pdf
140 http://nanomission.gov.in/;
141 http://timesofindia.indiatimes.com/home/science/Govt-approves-Rs-650-crore-for-Nano-mission/articleshow/30722422.cms
142 www.csir.res.in/
143 http://www.csir.res.in/external/heads/collaborations/NM.pdf
144 http://www.teriin.org/div/ST_BriefingPap.pdf
145 www.dst.gov.in/about_us/ar05-06/serc.htm
146 See also http://www.sciencedev.net/Docs/Iran_Nano.pdf (2010)
147 http://webarchive.nationalarchives.gov.uk/20090609003228/http://www.berr.gov.uk/files/file11959.pdf
148 http://statnano.com/report/s29
149 http://www.nanotech-now.com/news.cgi?story_id=45237
150 http://nano.ir/index.php?lang=2

researchers, having supported over 1400 researchers for nanotechnology activity between 2004 and 2010, at a cost of USD 12 million[151] (EUR 9 million[152]).

INIC has also funded the development of research and training facilities for nanotechnology research, such as the Institute for Nanoscience and Nanotechnology at the Sharif University of Technology. The INT, established in 2004, was the first such institute to offer a PhD in nanotechnology in Iran[153]. INIC undertakes education and awareness-raising activities including a students' Nano Club, seminars, workshops, publications and a multi-lingual (Arabic, Persian, Russian and English) website[154].

Also in 2004, INIC was instrumental in establishing the Iran Nanotechnology Laboratory Network to optimise Iran's nanotechnology infrastructure. Forty-two laboratories across Iran operate under the network. The role of INIC includes evaluation and ranking of member laboratories and providing support for them in areas such as training workshops, lab equipment, and in gaining accreditation as testing and calibration labs.

INIC operates through working groups on areas including Human Resource Development; Technology Development and Production; and Education and Awareness. It also addresses standards and regulations through the Iran Nanotechnology Standardisation Committee (INSC)[155], a body established in 2006 as a collaboration between the INIC and the Institute of Standard and Industrial Research of Iran (ISIRI)[156].

Continuing to support nanotechnology and the work of INIC, in 2005, a "Future Strategy" was adopted by the Cabinet as a 10-year nanotechnology development plan to run from 2005 to 2014. Its mission was to place Iran among the top fifteen advanced countries in nanotechnology in the world. The focus was placed on building and using infrastructure and human resources; improving communication and networking both within Iran and internationally; and generating economic added value from nanotechnology as a means of achieving economic development[157].

Internationally, in the context of the Economic Co-operation Organisation (ECO), Iran promoted the establishment in 2009 of an ECO Nanotechnology Network, both providing funding to establish the network and agreeing to co-ordinate it jointly with the ECO Secretariat. INIC is the Iranian representative on the network.

5.3.3 South-Eastern Asia

5.3.3.1 Malaysia

The Second National Science and Technology Policy (STP II), launched in 2003, identified nanotechnology and photonics as priority emerging technologies. In all, six targeted products and technologies were specified: photovoltaic (PV) solar cells, Li-ion batteries, plant vaccines, drug delivery systems, nano-biochips, and nano-biosensors.

The Malaysian National Nanotechnology Initiative (NNI) was established in 2006 to advance nanotechnology and related sciences by clustering local resources and knowledge of Malaysian researchers, industry and the government. The NNI paved way for the establishment in 2010 of the National Nanotechnology Directorate under the Ministry of Science, Technology and Innovation (MOSTI). The National Nanotechnology Directorate (NND)[158] facilitates nanotechnology development in Malaysia by acting as a central co-ordination agency. In 2011, the Top-down Nanotechnology Research Grant (NanoFund) was introduced and NanoMalaysia Centres of Excellence created. Among these are the Institute of Nano-electronics and Engineering (INEE)[159] (with a research focus on nano photonics including nano photonics devices, nano fluidics devices and quantum optical devices), and the Institute of Micro Engineering and Nano-electronics (IMEN), UKM[160] which focuses also on Photonics & Nano-photonics Technology.

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[151] http://www.nanotech-now.com/news.cgi?story_id=36557
[152] Average yearly conversion rate, 2004-2010 (*source*: www.wolframalpha.com)
[153] http://blogs.scientificamerican.com/guest-blog/science-and-sanctions-nanotechnology-in-iran/
[154] http://nano.ir/index.php?ctrl=static_page&lang=2&id=397&section_id=22
[155] http://nanostandard.ir/index.php?lang=2
[156] http://www.isiri.com/
[157] http://statnano.com/strategicplans/1
[158] http://www.mosti.gov.my/en/about-us/divisions-departments/national-nanotechnology-directorate-division-nnd/
[159] http://inee.unimap.edu.my/
[160] www.ukm.my/

To further support activity on these priority areas, the National Innovation Council of Malaysia in 2011 identified the need for a national organisation for nanotechnology commercialisation. NanoMalaysia[161] was created in 2011 as a company under the Ministry of Science, Technology and Innovation (MOSTI). It is responsible for commercialisation of nanotechnology research and development; industrialisation of nanotechnology; facilitation of investments in nanotechnology; and human capital development in nanotechnology.

5.3.3.2 The Philippines[162]

Nanotechnology was first identified as a priority area in the Philippines in 2009 when the Department of Science and Technology (DOST) formed of a multidisciplinary group to create a roadmap for the development of nanotechnology in the country. The Nanotechnology Roadmap for the Philippines identified five key sectors for the application of nanotechnology which also coincided with the priority areas of DOST for R&D support. These areas were: information and communications technology and semiconductors; energy; environment; food and agriculture; and health.

5.3.3.3 Singapore

With the aim of transitioning to a knowledge-based economy, Singapore has relied since the early 1990s on its five-year basic plans for science and technology (S&T). Foresight and technology scanning were key components of the process by which the 2010 plan[163] was developed. Thirteen technology scanning panels were established, one on 'Exploiting Nanotechnologies'. There were also panels on semiconductors, materials and infrastructure, manufacturing, information storage, intelligent systems, broadband, the grid, information management, energy, environmental technologies, engineering science in medicine, and frontiers in chemicals.

In the 2010 strategy document, the connection is made between the S&T Plan and the Manufacturing 2018 Plan Intelligent National Plans of Singapore's Economic Development Board[164], and the Roadmap (ITR5) of the Infocomm Development Authority[165]. It links nanotechnology research and development to industrial development and supports collaboration between industry, research institutes and universities. The aim is for an enhancement of applied research in nanotechnology to enable industrial clusters including electronics, ICT, chemicals, food, precision machinery, transportation machinery, environmental and engineering. The Plan also indicates nanotechnology is fundamental and horizontal to these clusters.

The principle funding agency for nanoscience and nanotechnology (NST) in Singapore is the Agency for Science, Technology & Research (A*STAR)[166]. A*STAR's Nanotechnology Initiative started in 2001 with the target of building on existing capabilities to develop specific areas of NST research always with applications and potential use by industry as a goal. A*STAR research institutes involved in NST include the Institute of Microelectronics (IME)[167]; the Data Storage Institute (DSI)[168]; the Institute of Manufacturing Technology (SIMTech); the Institute of Materials Research and Engineering (IMRE)[169]; and the Institute of Bioengineering and Nanotechnology (IBN)[170]. The photonics research activities of IME are strongest in its Nano-Electronics and Photonics (NanoEP) Programme[171]. IME collaborates with industry in the silicon photonics platform, based on 248 nm deep UV lithography supporting a wide range of submicron photonic devices and structures[172].

DSI research is structured in four research areas, one of them is on advanced concepts and nanotechnology that aims to develop tools and technologies in nanophotonics, plasmonics and fibre optics, integrated lasers and other on-chip photonic solutions, quantum optics, spintronics and micromagnetics. DSI facilities includes customised R&D equipment for specific applications, to mass-production capable tools to support industrial process development and technology transfer and a 400 m^2 cleanroom for nano-electrophotonics integration.

In 2010, A*Star's SIMTech launched the Nanotechnology in Manufacturing Initiative (NiMI) to foster

[161] http://www.nanomalaysia.com.my/index.php?p=aboutus&c=whoweare
[162] http://www.techmonitor.net/tm/images/d/d1/10jan_feb_sf3.pdf
[163] https://www.mti.gov.sg/ResearchRoom/Pages/Science-and-Technology-Plan-2010.aspx
[164] www.edb.gov.sg
[165] www.ida.gov.sg
[166] www.a-star.edu.sg/
[167] https://www.a-star.edu.sg/ime/
[168] www.a-star.edu.sg/dsi/
[169] www.a-star.edu.sg/imre
[170] www.ibn.a-star.edu.sg/
[171] https://www.a-star.edu.sg/ime/RESEARCH/NANO-PHOTONICS-PROGRAMME.aspx
[172] https://www.a-star.edu.sg/ime/SERVICES/silicon_photonics.aspx

collaborative efforts between research and industry, developing industrial capability and enhancing competitiveness.

In Singapore, nanotechnology is also a key area for the Science and Engineering Research Council (SERC) and the Biomedical Research Council.

5.3.3.4 Thailand

Thailand has been active in nanotechnology since at least 2003 when it established NANOTEC[173] as the leading national agency for nanotechnology development. It operates under the jurisdiction of the National Science and Technology Development Agency (NSTDA) and the Ministry of Science and Technology (MOST), one of four such agencies. The guiding principle of NANOTEC is to contribute to society, increase Thailand's competitiveness, and improve the quality of life and the environment of the people of Thailand through research and development in nanoscience and nanotechnology. NANOTEC undertakes and supports research, development, design and engineering in nanotechnology, and the transfer of the resulting technology to industry and the marketplace. In 2013, the Central Laboratory of NANOTEC consisted of 12 units located at the Thailand Science Park. These covered areas including nanomaterials for energy and catalysis, integrated nanosystems, hybrid nanostructures and nanocomposites; nanoscale simulation; functional nanomaterials and interfaces; nano characterisation; and engineering and manufacturing characterisation.

In 2012, the National Nanotechnology Policy Framework (2012-2021)[174] and the Nanosafety and Ethics Strategic Plan (2012-2016)[175] were approved by government for implementation by the Ministry of Science and Technology, and relevant agencies. The Framework has three primary goals:

- Improving agricultural technology and manufacturing industry that meet the demand of the market through nanotechnology;
- Utilising nanotechnology to develop materials, products, and equipment in order to enhance the quality of life, wellness, and environment; and
- Becoming ASEAN's leader in nanotechnology research and education.

The overall strategic direction of the Framework encompasses four target clusters, including electronics, energy and environment, and food and agriculture, and defines seven flagship products including nano-electronics (photovoltaic films) and nano-sensors for medical diagnostics. It aims to achieve its goals through actions in human resources, research and development, infrastructure development, management (of quality, safety and standards) and technology transfer.

The strategy in Thailand is largely to focus on product development through nanotechnology. To this end, NANOTEC is addressing national and NSTDA priorities under the Framework through seven flagship programmes to develop specific products.

With regards to photonics, the Mahidola University hosts the Centre of Nanoscience and the nanotechnology research unit (a centre of excellence). One of its research area is molecular electronics and photonics (including photoluminescence and electroluminescence phenomena of organic materials, especially for the making of organic light-emitting device (OLED)). An interdisciplinary research approach combines polymer chemistry (to synthesise the new organic materials), physics (understanding electroluminescence phenomena) and electrical engineers (to optimise the device performance)[176].

5.3.4 Western Asia

5.3.4.1 Israel

The first Israeli nanotechnology policy initiative was the establishment of the Israel Nanotechnology Initiative (INNI)[177] in 2002 as a shared action of the Forum for National Infrastructures for Research & Development (TELEM)[178] and the ministry for the economy (now called the Ministry for Industry, Trade and Labour)[179]. INNI's mission is "to make nanotechnology the next wave of successful industry in Israel by creating an engine for global leadership". To achieve this, actions have been

[173] http://www.nanotec.or.th/th/wp-content/uploads/2013/05/NANOTEC-brochure11.pdf
[174] http://www.nanotec.or.th/en/wp-content/uploads/2012/02/The-National-Nanotechnology-Policy-framework exe-sum.pdf
[175] http://www.nanotec.or.th/en/
[176] http://www.sc.mahidol.ac.th/research/nano.htm
[177] http://www.nanoisrael.org/
[178] http://www.trdf.co.il/eng/fundinfo.php?id=2846
[179] http://www.economy.gov.il/English/Pages/default.aspx

taken on scientific research in nanoscience and nanotechnology (NST); on increasing public-private collaboration on NST; on speeding up commercialisation of NST; and on leveraging funding from both public and private sources to support NST in Israel. INNI is closely linked to the national system with its Director appointed by the Chief Scientist at the Ministry and the Board operating out of the MAGNET Programme[180] at the Office of the Chief Scientist.

Since NST was identified as a national priority area in 2007, the areas that have been targeted have included research infrastructure, training Israeli scientists in NST, attracting foreign researchers to work in Israeli institutions, increasing collaboration in NST and publication output of the highest international standard, fostering public-private partnerships and knowledge transfer and commercialisation of NST. Investment has been running at about USD 20 million (EUR 15.5 million[181]) per annum for basic NST equipment plus another almost USD 10 million (EUR 8 million[182]) per annum for new infrastructure and facilities.[183] The aim has been to create a sustainable basis for NST within the universities via training, recruitment and the provision of facilities on the basis that, without a strong research base, direct investment in technology will not be able to generate the required returns in terms of technology development and deployment.

The Triangle Donation Matching (TDM) programme[184] was launched under the INNI in 2006, a 5-year national programme to support NST research infrastructure in six universities in Israel. A total of USD 250 million (EUR 198 million[185]) has been invested by Israeli Universities, private donors and the Israeli government to recruit leading nano-scientists and acquire equipment, facilities and labs for six nano-centres at the Universities. The first impact was seen in 2005 at Technion, Israel's Institute of Technology[186, 187], the other five research universities receiving support in 2006. One of these is the Hebrew University Centre for Nanoscience and Nanotechnology whose focus areas includes nano-optronics for sensing and communication applications and nanomaterials for industrial applications and also has a specialisation in sol-gel-based nanomaterials. Furthermore, photonics and electronics is among the research activities of the Ilse Katz Institute for Nanoscale Science and Technology, at Ben-Gurion University, with a specialisation in design, simulation and fabrication of nano-photonic chips and devices[188].

To help academics and industry to access the facilities of the six Israeli nano centres, the INNI has made available a national nano infrastructure catalogue[189]. The catalogue of equipment includes pricing for the use of the equipment and contact information. Industry users are supported by the university nano-centres to enable them to be effective in using their R&D equipment.

INNI also has introduced the Industry-Academia Matchmaking programme to make Israeli nanotechnology more visible to the industrial and investment communities and to promote Israel's NST research capabilities to potential partners. Experts help potential collaborators to meet, access expertise and access funding depending on their needs. They engage with key nanotechnology stakeholders in Israel and abroad, initiate and managing national and international networks in NST. They also gather statistics and market information on NST.

5.3.4.2 Saudi Arabia[190]

In 2002, Saudi Arabia decided to build further on the work of the King Abdul Aziz City for Science and Technology (KACST), the Kingdom's main agency for promoting research and development, established in 1985. It put in place a National Policy for Science and Technology (NPST) with plans to increase R&D funding to 1.6% of GDP. KACST was made responsible for implementing the policy

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[180] http://www.moital.gov.il/NR/exeres/111E3D45-56E4-4752-BD27-F544B171B19A.htm
The Magnet programme supports companies and academics to form consortia to research precompetitive generic technologies. Direct funding is up to 66% of the cost of the project with no obligation to repay royalties.
[181] Average yearly conversion rate, 2012 (*source*: www.wolframalpha.com)
[182] Ibid
[183] Figures for funding under the programme to 2012.
[184] http://www.nanoisrael.org/category.aspx?id=1278
[185] Average yearly conversion rate, 2006 (*source*: www.wolframalpha.com)
[186] The Technion centre was co-funded by the Russel Berrie Foundation via a donation of USD 26 million which, together with funding from Technion itself, the Office of the Chief Scientist and the Ministry of Finance, made up to USD 78 million for the Russell Berrie Institute for Research in Nanotechnology.
[187] Israel Institute of Technology http://www.technion.ac.il/en/
[188] http://in.bgu.ac.il/en/iki/Pages/Research-Activity1.aspx
[189] http://www.nanoisrael.org/category.aspx?id=13671
[190] A review of nanotechnology development in the Arab World, Bassam Alfeeli et al., Nanotechnology Review, 2013 (05/2013; 2(3):359-377)

which included 5-year strategic plans (missions) in eleven research areas prioritising nanotechnology and advanced materials (as well as photonics, electronics, water, information technology, oil and gas, petrochemicals, biotechnology, space and aeronautics, energy and environment). The National Nanotechnology Programme (NNP) was established to deliver the plan in that area.

During the implementation of the NNP, nanotechnology centres began to be established such as the Centre of Excellence in Nanotechnology (CENT) established 2005 at the KFUPM[191]; and the CNT established in 2006 at the KAU[192]. These centres operated in the context of the multidisciplinary programme of Strategic Priorities for Nanotechnology 2008-2012, put in place by the Saudi Arabian Ministry of Economy and Planning in 2008.

Additional nanoscience and nanotechnology centres followed. The Centre of Excellence of Nano-manufacturing Applications (CENA) was established in 2009 at KACST and the King Abdullah Institute for Nanotechnology (KAIN)[193] established in 2010 at the KSU in the Riyadh Techno Valley. The KAIN covers different areas including telecommunications, energy, manufacturing and nanomaterials, medicine and pharmaceuticals, food and environment, and water treatment and desalination. Companies such as the Saudi National Oil Company (established as an Arabian American Oil Company, known now as Saudi ARAMCO) and the Saudi Basic Industries Corporation (SABIC) are collaborating on nanotechnology research with the nanotechnology centres. There are more than 20 projects in the field of nanotechnology for these two companies alone.

5.3.4.3 Turkey

Nanotechnology was one of eight strategic fields of research and technology identified in the Vision 2023 Technology Foresight Study prepared by the Supreme Council of Science and Technology (SCST) in 2002. The Foresight Study formed part of the development of the National Science and Technology Policies 2003-2023 Strategy Document. In nanotechnology, seven thematic priority areas were selected: (i) nano-photonics, nano-electronics, nano-magnetism; (ii) nano-sized quantum information processing (iii) nanomaterials; (iv) fuel cells, energy; (v) nano-biotechnology; (vi) nano-characterisation; and (vii) nanofabrication. Nanotechnology was also included as a priority technology field in the Development Programme prepared by State Planning Organisation (SPO) for the period 2007-2013.

Projects in nanotechnology are supported by the Scientific and Technological Research Council of Turkey (TUBITAK) and the Ministry of Development (MoD and between 2007 and 2014 it is estimated[194] that nanotechnology has received State support of about one billion Turkish Lira, or c. USD 500 million (EUR 367 million[195]). Over 20 nanotechnology research centres, departments and graduate schools have been established including NanoTam[196] and Unam[197] (with research areas that includes nano-photonics, fibre optics and lasers) at Bilkent University; Sabanci University Nanotechnology Research and Application Centre (SUNUM)[198]; and the Micro and Nanotechnology Department at the Middle East Technical University[199].

5.4 Oceania

5.4.1.1 Australia

The National Nanotechnology Strategy (NNS) was put in place by the Australian Department of Innovation, Industry, Science and Research in 2007 as a dedicated strategy for nanotechnology in 2007 to 2009. The Australian Office of Nanotechnology was established to co-ordinate the strategy and ensure a whole-of-government approach to nanotechnology issues. A Public Awareness and Engagement Programme formed part of the NNS.

In 2009-2010, the NNS was replaced with a National Enabling Technology Strategy (NETS) a comprehensive national framework for the safe and responsible development of novel technologies (including nanotechnology and biotechnology). With funding over four years of AUS 38.2 million (EUR

[191] King Fahd University of Petroleum and Minerals, Riyadh
[192] King Abdul Aziz University, Jeddah
[193] http://nano.ksu.edu.sa/en
[194] http://www.issi2015.org/files/downloads/all-papers/0720.pdf
[195] Average yearly conversion rate, 2007-2014 (*source*: www.wolframalpha.com)
[196] http://www.nanotam.bilkent.edu.tr/eng/main.html
[197] http://unam.bilkent.edu.tr/?page_id=576
[198] http://sunum.sabanciuniv.edu/
[199] http://mnt.metu.edu.tr/

28.3 million[200]), the strategy aimed to ensure good management and regulation of enabling technologies in order to maximise community confidence and community benefits from the commercialisation and use of new technology. Public engagement has remained an important topic in Australia for nanotechnology and other novel technologies.

In 2012, the National Nanotechnology Research Strategy[201] was prepared by the Australian Academy of Science, using funding received from the National Enabling Technologies Policy Section in the Department of Industry, Innovation, Science, Research and Tertiary Education. The Research Strategy highlighted the importance of developing nanofabrication capabilities necessary to have a major impact on all areas of information and communication technology (ICT) through the fabrication of quantum/nanoscale photonic, electronic and electromechanical structures. In addition, it stressed Australia as being a world leader in optical fibres (through its Institute for Photonics and Advanced Sensing[202], Institute of Photonics and Optical Science[203] and Australian National Fabrication Facility (ANFF)[204]). Other photonics related areas mentioned are electron beam lithography and nanowires based on III-V compounds (fundamental for the development of next-generation photonics). More in general, the Strategy set out a vision for Australia to become a world leader in a nanotechnology-driven economy with a strong nanotechnology research base and the means to assist industry to revolutionise its portfolio through nanotechnology, for greater competiveness and to address the grand challenges most relevant to Australia. The Strategy highlighted the importance of infrastructure, interdisciplinary research, international engagement, the translation of research, and the growth of SMEs.

Australia also operates a network to link research facilities across the country, the Australian Nanotechnology Network[205]. The Network was established by bringing together four seed funding networks. It comprises about 1,000 active researchers from universities, institutes and government research organisations, half of whom are students. Its aims are to promote collaboration, increase multidisciplinary awareness and collaboration, foster forums for postgraduate and early career researchers, increase and improve awareness of nanotechnology infrastructure, and promote international links.

5.4.1.2 New Zealand

New Zealand began by taking a networking approach to nanotechnology, led by the MacDiarmid Institute for Advanced Materials and Nanotechnology[206]. The Institute, formed in 2002, is a partnership between five Universities and two Crown Research Institutes in Auckland, Palmerston North, Wellington, Christchurch and Dunedin. It was awarded USD 23.2 million (EUR 19 million[207]) funding for 2003-2006 from the Ministry of Education and, in early 2006, developed a "Nanotechnology Initiative for New Zealand"[208] identifying where capability in nanotechnology could be developed in the country. The Initiative identified six programmes for nanoscience and nanotechnology research: nano-photonics, nano-electronics and nano-devices; nanotechnology for energy; nano- and micro-fluidics; nanomaterials for industry; bio-nanotechnologies; and social impacts of nanotechnology.

Also in 2006, the New Zealand government released a Nanoscience and Nanotechnologies Roadmap (2006-2015)[209]. Highlighting international and national research, the Roadmap placed nanotechnology amongst government's strategic priorities, setting high level directions for nanotechnology-related research and policy in New Zealand. Among the key sectors some potential areas and type of applications were identified. Some sectors are relevant for photonics, for instance ICT (including optical signalling) and Electronic and components (including photonic crystals and optical computing). Three priority areas for public funding were identified: the creation of new materials, diagnostic devices; and tools and techniques. The Roadmap, in identifying the existing strengths, assigned crucial importance to the programme on nano-photonics, nano-electronics and nano-devices, included in the Nanotechnology Initiative for New Zealand. The Ministry of Science

[200] Average yearly conversion rate, 2010-2013 (*source*: https://www.ecb.europa.eu/stats/exchange/eurofxref/html/eurofxref-graph-aud.en.html)
[201] https://www.science.org.au/publications/national-nanotechnology-research-strategy
[202] http://www.adelaide.edu.au/ipas/about/role/
[203] http://sydney.edu.au/ipos/
[204] http://www.anff.org.au/
[205] http://www.ausnano.net/index.php?page=home
[206] http://www.macdiarmid.ac.nz/
[207] Average yearly conversion rate, 2003-2006 (*source*: www.wolframalpha.com)
[208] http://www.macdiarmid.ac.nz/a-nanotechnology-initiative-for-new-zealand/
[209] http://statnano.com/strategicplans/13

and Innovation was in charge of policy action to implement the Roadmap.

The Ministry of Science and Innovation Statement of Intent 2011-14 highlighted two high-level priorities – growing the economy and building a healthier environment and society. In addition to the traditional resource sectors of New Zealand, it sought to capability in knowledge-intensive activities, such as high-technology manufacturing and the services sector. Six priority areas were identified including energy and minerals, high-value manufacturing and services, health and society, as well as biological sciences, hazards and infrastructure, and the environment[210].

5.5 Africa

5.5.1.1 South Africa

Since 2002, the Republic of South Africa has launched several national nanotechnology initiatives to strengthen national capabilities in this field. Relevant steps have included

- In 2002, the formation of the South African Nanotechnology Initiative (SANi)[211] with membership comprising of academics, researchers, engineers, private sector companies, and research councils.
- In 2003, the launching of South Africa's Advanced Manufacturing Technology Strategy (AMTS)[212] by the Department of Science and Technology (DST).
- In 2005, the publication of the National Strategy on Nanotechnology (NSN)[213] by the DST. The strategy focuses on four areas:
  - establishing characterisation centres (national multi -user facilities);
  - creating research and innovation networks (to enhance collaboration: inter-disciplinary, national and internationally);
  - building human capacity (development of skilled personnel); and
  - setting up flagship projects (to demonstrate the benefits of nanotechnology towards enhancing the quality of life, and spurring economic growth).

South Africa launched its first nanotechnology innovation centres in 2007 at the CSIR[214] and MINTEK[215]. Each centre has developed collaborative research programme, often with other national institutions. These include programmes in designing and modelling of novel nano-structured materials, at the CSIR- National Centre for Nano-structured Materials (NCNSM)[216], and work on the application of nanotechnologies in the fields of water, health, mining and minerals at MINTEK.

In addition to engaging with European researchers through Framework Programmes, South Africa has established international collaboration mechanisms which include nanotechnology with other developing countries, e.g. the India–Brazil-South Africa (IBSA) partnership[217] enables joint projects and mobility[218] between S&T departments in those countries.

The sections that follow look at publications and patenting on nanotechnology photonics.

[210] http://www.mbie.govt.nz/
[211] http://www.sani.org.za/
[212] http://www.esastap.org.za/download/natstrat_advmanu_mar2005.pdf
[213] http://chrtem.nmmu.ac.za/file/35e56e36b6ab3a98fac6fc0c31ee7008/dstnanotech18012006.pdf
[214] http://www.csir.co.za/
[215] http://www.nic.ac.za/
[216] http://ls-ncnsm.csir.co.za/
[217] http://www.ibsa-trilateral.org/
[218] http://www.ibsa-trilateral.org/about-ibsa/areas-of-cooperation/people-to-people

6 PUBLICATIONS IN NANOTECHNOLOGY AND PHOTONICS

6.1 Overview

In the period 2000 to 2014, around 86,000 were identified are relating to both nanotechnology and photonics. This volume of publications is equivalent to around 5% of the output for nanoscience and nanotechnology (NST), about 1.8 million between 2000 and 2014.

The table below shows the publication output between 2000 and 2014 with over 112,000 NST publications having been identified relating to both nanotechnology and photonics globally. Over 36,000 publications on nanotechnology/photonics were produced in EU 28 plus EFTA countries (EU28&EFTA, includes Switzerland and Norway), 32% of the total World nanotechnology/photonics publications in the time-period 2000-2014. The share of EU28&EFTA has gradually decreased over time from over 40% to around 30%.

Table 6-1: Annual NST publication output for nanotechnology photonics worldwide and in the EU28&EFTA, 2000-2014

Year	World	EU 28 & EFTA	
	npub	npub	%
2000	1,820	798	43.8%
2001	2,072	891	43.0%
2002	2,421	1,022	42.2%
2003	2,822	1,103	39.1%
2004	3,239	1,227	37.9%
2005	4,167	1,481	35.5%
2006	4,735	1,627	34.4%
2007	5,366	1,771	33.0%
2008	6,050	1,987	32.8%
2009	6,413	2,113	32.9%
2010	7,203	2,261	31.4%
2011	8,330	2,595	31.2%
2012	9,315	2,989	32.1%
2013	10,576	3,110	29.4%
2014	11,530	3,232	28.0%
TOTAL	**86,059**	**28,207**	**32.8%**

Source: Derived from Web of Science

There has been a high level of growth in nanotechnology/photonics publications as indexed to the year 2000. For the World, there has been almost a six-fold growth while for the EU28&EFTA, it is around a four-fold growth.

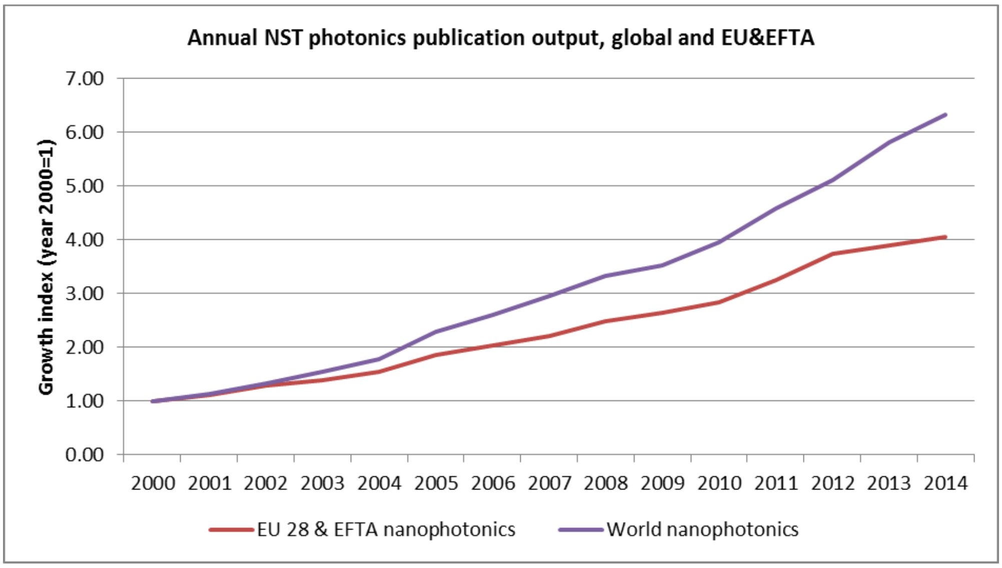


Figure 6-1: Annual NST publication output on nanotechnology/photonics, worldwide and EU28&EFTA, 2000-2014

Looking at the EU28&EFTA proportion of world output on nanotechnology/photonics, it is seen to have decreased over time, as shown below. This is mainly caused by a sharp increase in the output from China.

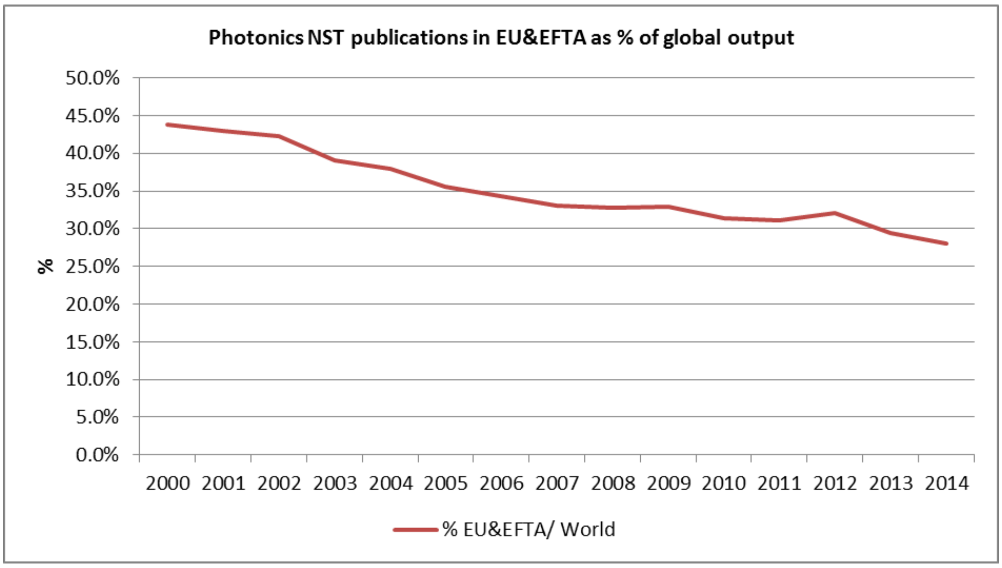


Figure 6-2: Nanotechnology/photonics publications as a percentage of World total, 2000-2014

The table below shows the journals in which researchers in this sector most frequently published their results. The results show a clear preference for the top three journals.

Table 6-2: Most common journals for nanotechnology/photonics publications, 2000-2014

Rank	Journal	npub
1	Applied Physics Letters	5299
2	Optics Express	4202
3	Physical Review B	4163
4	Journal of Applied Physics	2522
5	Journal of Physical Chemistry C	2137
6	Nano Letters	1972
6	Optics Letters	1523
8	Langmuir	1350
9	Physical Review Letters	1194
10	Nanotechnology	1079

6.2 Activity by region and country

The most prolific region for nanotechnology/photonics publications in 2014 (the most recent year for data collection) (calculated from the table of the top 25 publishing countries) was Asia, followed by EU28 & EFTA and North America. The most prolific country for nanotechnology/photonics publications globally in 2014 was China (PRC), followed by the US, Germany, India and Japan.

Table 6-3: Most prolific regions for nanotechnology/photonics publications, 2014

Region	npub
Asia	5625
EU 28 plus EFTA	3232
North America	2875
Middle East	436
Oceania	334

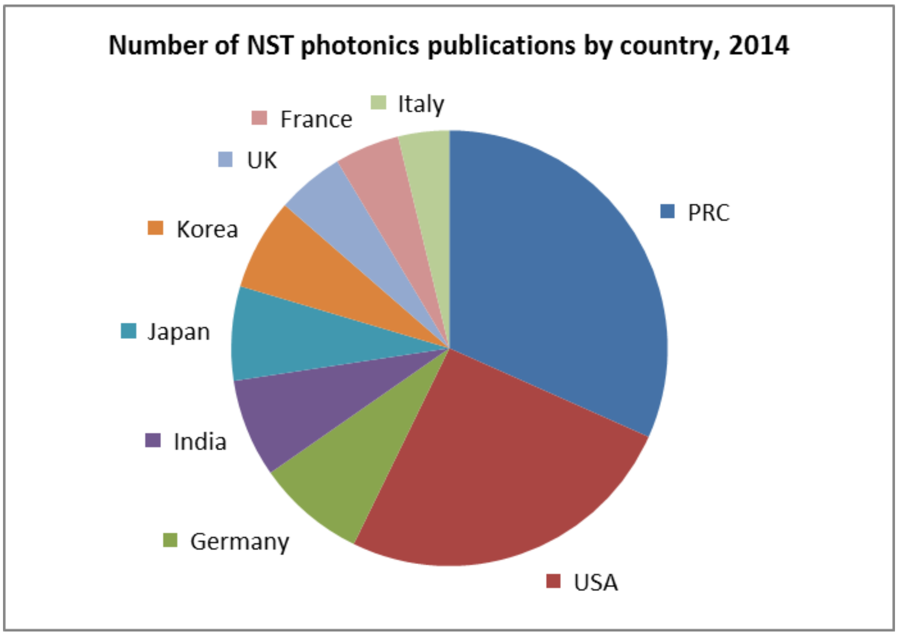


Figure 6-3: Number of nanotechnology/photonics publications by country (top 9), 2014

Table 6-4: Number of nanotechnology/photonics publications by country (top 20), 2014

Country	Region	npub
PRC	Asia	3243
USA	North America	2616
Germany	EU28 & EFTA	828
India	Asia	747
Japan	Asia	716
South Korea	Asia	697
United Kingdom	EU28 & EFTA	512
France	EU28 & EFTA	492
Italy	EU28 & EFTA	388
Spain	EU28 & EFTA	387
Singapore	Asia	364
Canada	North America	331
Australia	Oceania	325
Netherlands	EU28 & EFTA	181
Sweden	EU28 & EFTA	178
Switzerland	EU28 & EFTA	154
Saudi Arabia	Middle East	142
Poland	EU28 & EFTA	138
Turkey	Middle East	134
Denmark	EU28 & EFTA	112

In the EU28&EFTA, Germany generated the largest number of publications in 2014, followed by the United Kingdom, France, Italy and Spain, as shown below.

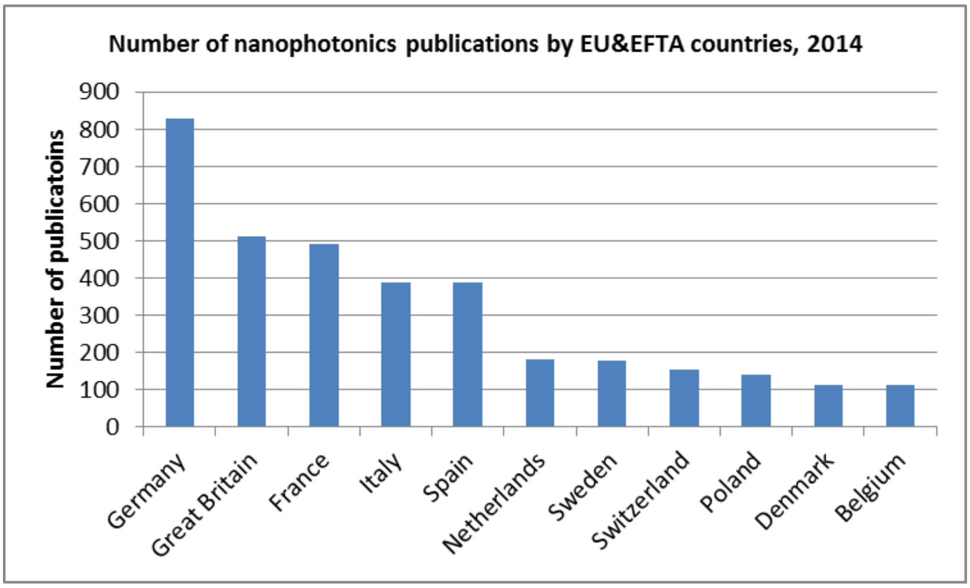


Figure 6-4: Number of nanotechnology/photonics publications by top EU&EFTA countries, 2014

6.3 Activity by organisation type

The most active organisations in NST photonics publications in 2014 are shown in the table below. The higher education organisations with the most nanotechnology photonics publications globally in 2014 were predominantly Asian universities as shown in the table below of the top 25 publishing organisations. The highest performing non-Asian universities were MIT, the University of California Berkeley, Stanford University, Harvard University (all in the US) and the University of Cambridge and Imperial College London (both in the United Kingdom).

Table 6-5: Publication numbers for nanotechnology/photonics for higher education and research organisations, 2014

Country	University/ Research Institute	npub
PRC	Chinese Academy of Sciences	560
Singapore	Nanyang Technology University	178
PRC	Jilin University	135
PRC	Peking University	126
PRC	Zhejiang University	125
Singapore	Natl University Singapore	117
USA	MIT	112
PRC	Nanjing University	112
PRC	Huazhong University of Science and Technology	104
USA	University of Calif Berkeley	103
PRC	University of Science and Technology China	100
PRC	Southeast University	96
United Kingdom	University of Cambridge	96
PRC	Tsinghua University	90
USA	Stanford University	90
Japan	University of Tokyo	90
India	Indian Inst Technology	87
United Kingdom	Imperial College London	87
Singapore	Astar[219]	87
Korea	Seoul National University	86
USA	Harvard University	82
Korea	Korea Advanced Institute of Science and Technology	82
USA	Northwestern University	79
USA	University of Texas Austin	76
PRC	Soochow University	75

The higher education organisations (EU and EFTA) with the most nanotechnology/photonics publications globally in 2014 were the University of Cambridge, Imperial College London and the Technical University of Denmark, as shown in the table below of the top ten NST publishing organisations for nanotechnology/photonics publications.

[219] AStar is the funding agency Singapore (classified as a University/ Research Institute by Web of Science)

Table 6-6: Number of nanotechnology/photonics publications by organisation (top ten), 2014

Organisation	Country	npub
University of Cambridge	UK	96
Imperial College London	UK	87
Technical University of Denmark	DK	70
University Paris XI Sud	FR	64
Swiss Federal Institute of Technology (EPFL)	CH	63
Eindhoven University	DE	51
IIT Foundation (Istituto Italiano di Tecnologia)	IT	49
Linkoping University	SE	48
University of Jena	DE	47
Chalmers University	SE	45

The companies with the most nanotechnology/photonics publications globally in 2014 were IBM, Nippon Telegraph, Samsung Electronics Company (with Samsung Advanced Institute of Technology also appearing, lower in the table), and Philips, as shown in the table of the top publishing companies below.

Table 6-7: Number of nanotechnology/photonics publications by company (top eight), 2014

Company	Npub
IBM Corporation	28
Nippon Telegraph (NTT)	25
Samsung Electronics Co.	14
Philips	11
Hewlett Packard Corp	7
Omega Optical Inc.	7
Samsung Advanced Institute of Technology	6
AMO GmbH[220]	6

The next section goes on to look at the patenting activity in nanotechnology/photonics, over time, by country of applicant, by applicant organisation and by patents granted.

[220] https://www.amo.de/about-amo/

7 PATENTING IN NANOTECHNOLOGY AND PHOTONICS

7.1 Overview

This section looks at the patenting activity in nanotechnology/photonics by patent filings and patents granted over the time-period 1999-2011 at the leading global patent offices and by country of applicant and country of inventor, and by organisation including companies.

The patents and patent families (groups of patents related to the same invention) were identified by searching using the combination of keywords (identified within the NanoData project for the sector, see Annex) and IPC (International Patent Classification) numbers. The IPC numbers used were both those for nanotechnology i.e. B82 (or B82Y for manufactured nanomaterials) and those related to the sector under consideration (photonics, health, energy, etc.)[221]. The patent family to which the patents belonged was identified and all the patents in the patent families were retrieved.

The search was made for patents registered at the USPTO (US Patent and Trademark Office), EPO (European Patent Office) and WIPO (World Intellectual Property Organisation) thereby identifying USPTO, EPO and PCT applications. PCT[222] applications registered at WIPO are protected under the Patent Cooperation Treaty (PCT), an international treaty that enables the filing of patents to protect inventions in the countries[223] that are members of the treaty.

7.2 Number and evolution over time of photonics nanotechnology patent families

Using the above methodology for nanotechnology and for photonics, 44,391 (simple) nanotechnology patent families[224,225] of granted patents and patent applications were found in the period 1993-2011[226]. All were from the European Patent Office (EPO), US Patent and Trademark Office (USPTO) or the World Intellectual Property Organisation (WIPO)[227].

In the same period, the number of photonics patent families identified among the nanotechnology patents was 1,693, 3.8% of all nanotechnology patent families. As applications may have been filed with multiple authorities, the percentages for PCT, EP and US do not sum to 100%. The highest percentage of applications relating to nanotechnology/photonics is in the US (90.9%) and the lowest at the EPO (38.9%), the difference being more than a factor of two.

Table 7-1: Absolute numbers and percentages of patents on nanotechnology/photonics

Nanotechnology and Photonics Applications (1993-2011)	Absolute Number	Percentage
Total Patent Families	1,693	100%
PCT Applications	972	57.4%
EPO Applications	658	38.9%
USPTO Applications	1,539	90.9%

The figure below shows the evolution over time of patent applications to WIPO (PCT), the EPO or USPTO as measured by the percentage of patent families. The shape of the trend line is very similar in all three cases, rising most sharply in the period 1999-2002 and dropping particularly sharply from

[221] Thus all patent documents including at least one of the keywords (in title or abstract) was found but only when the patent was classified as being related to at least one of the sectorial IPC codes.
[222] http://www.wipo.int/pct/en/
[223] By filing one international patent application under the PCT, applicants can simultaneously seek protection for an invention in 148 countries throughout the world. http://www.wipo.int/pct/en/pct_contracting_states.html
[224] Here the definition of simple family is where all documents having exactly the same priority or combination of priorities belong to one patent family (http://www.epo.org/searching/essentials/patent-families/definitions.html). The patent families include at least one PCT, EPO or USPTO patent application.
[225] A patent family is defined by WIPO (the World Intellectual Property Organisation) as a set of patent applications inter-related by either priority claims or PCT national phase entries, normally containing the same subject matter. http://www.wipo.int/
[226] This year refers to the oldest year of the priority patents.
[227] While patents can be filed in individual patent offices, many inventors choose to file applications under the Patent Classification Treaty (PCT). All WIPO applications are PCT applications.

2009 on in the USPTO.

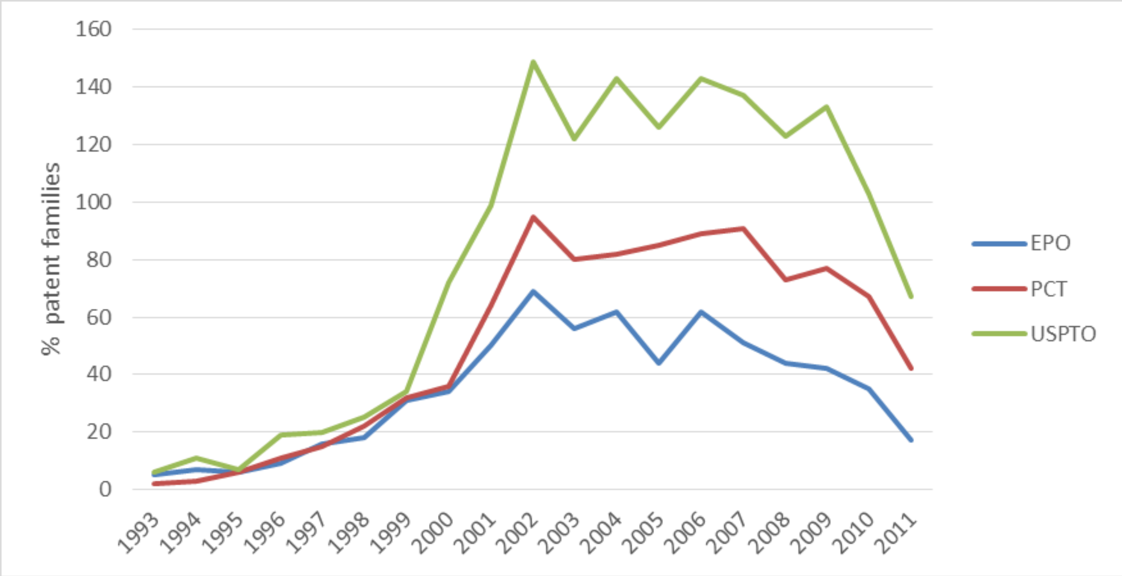


Figure 7-1: Evolution over time of EPO, WIPO (PCT) and USPTO nanotechnology/photonics patenting

7.3 Activity by filing country and region

By looking at PCT applications, it is possible to obtain an indication of the relative patenting activity of countries and regions. The top ten patent authorities through which PCT applications were filed are shown in the table, the US being by far the most prolific, followed by Japan, Europe (EPO) and the UK.

Table 7-2: Number of nanotechnology/photonics patent families by PCT receiving authority

Receiving authority	No. of Patent families (1993-2011)
United States	451
Japan	147
European Patent Office (EPO)	79
United Kingdom (GB)	75
International Bureau (WIPO)	37
Canada	30
South Korea	27
Germany	26
France	25
Denmark	15

7.4 Activity by country of applicant

PATENT APPLICATIONS

The total numbers of patent applications are shown below. Applicants may file patents with more than one patent authority, e.g. at the USPTO and as a PCT.

Table 7-3: NST photonics patent families, EU&EFTA and RoW, 1993-2011

	EU28 & EFTA	Rest of World
Number of nanotechnology/photonics patent families	835	2,213
Percentage of nanotechnology/ photonics patent families	28.8%	76.4%

The table below shows the data for the top 25 countries of applicants, as well as indicating the percentage of patent families by patent authority. EU28 and EFTA countries are marked in bold. As patents may be filed with more than one authority (including PCT, US and EP applications), the percentages can sum to more than 100%.

By far the highest number of patent families is found where the country of the applicant is the US. Japan, Germany and the UK have the next highest number of applicants, followed by Korea. In terms of applicants from Europe, Germany and the UK are followed by France, the Netherlands, Spain and Italy, Denmark and Sweden all with over 20 patent families. For Asia, the lead country for applicants, Japan (398), is followed by Korea (95), Taiwan (Chinese Taipei, 46), China (30) and India (9).

Table 7-4: Patent families by country of applicant, numbers and percentages, 1993-2011

	Country of applicant	No. of Patent Families	PCT	US	EP
1	US	786	60%	92%	31%
2	JP	398	40%	88%	35%
3	DE	133	64%	71%	64%
4	UK	123	73%	67%	50%
5	KR	95	31%	89%	26%
6	FR	91	56%	74%	73%
7	CA	68	57%	78%	31%
8	TW	46	2%	98%	4%
9	NL	35	71%	71%	77%
10	CN	30	43%	80%	10%
11	ES	27	63%	59%	30%
12	IT	26	62%	65%	85%
13	SG	24	46%	63%	33%
14	DK	23	70%	61%	57%
15	SE	20	65%	65%	35%
16	IL	16	63%	94%	38%
17	CH	14	50%	64%	64%
18	RF	14	64%	64%	57%
19	BE	13	38%	100%	69%
20	IN	9	78%	89%	22%
21	AU	7	71%	71%	14%
22	IE	6	50%	50%	33%
23	NO	6	50%	83%	33%
24	AT	5	20%	100%	40%
25	FI	5	100%	40%	20%

92% of patents of US applicants are filed with the USPTO while 60% are filed as PCTs. Only 31% are filed by US applicants at the EPO.

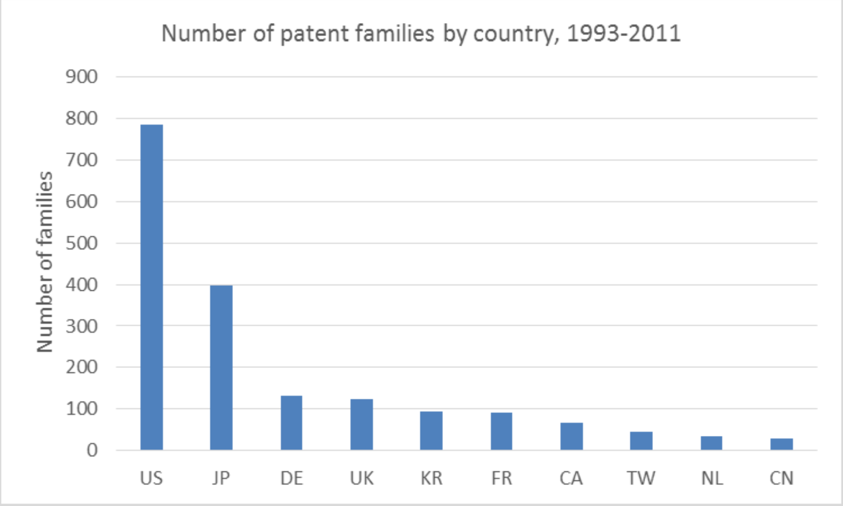


Figure 7-2: Number of patent families by country of applicant (top ten), 1993-2011

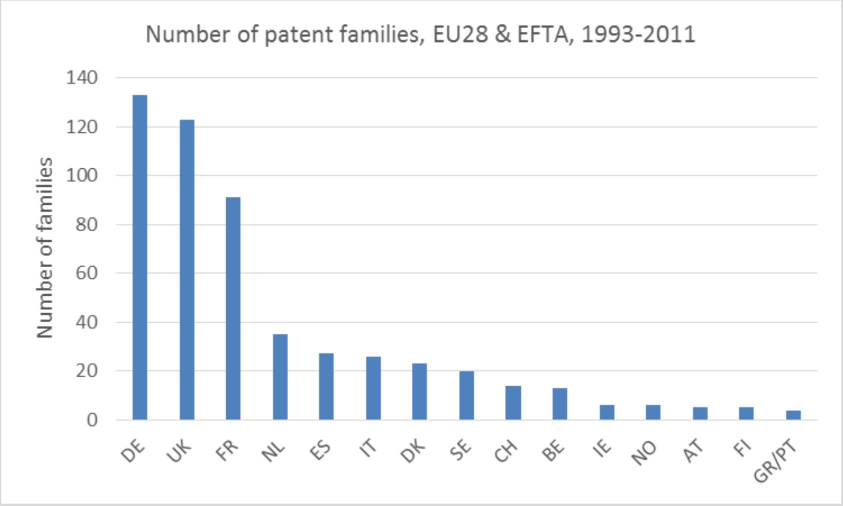


Figure 7-3: Number of patent families for EU28 & EFTA countries, 1993-2011

For the EU28 & EFTA countries, Germany, the UK and France lead significantly over the following group of the Netherlands, Spain, Italy, Denmark and Sweden. Greece and Portugal have the same number of patent families (4).

Looking at the non-European and non-US countries of applicants, Japan (398) strongly leads the way with over four times the patent families of the next countries, Korea (95) and Canada (68).

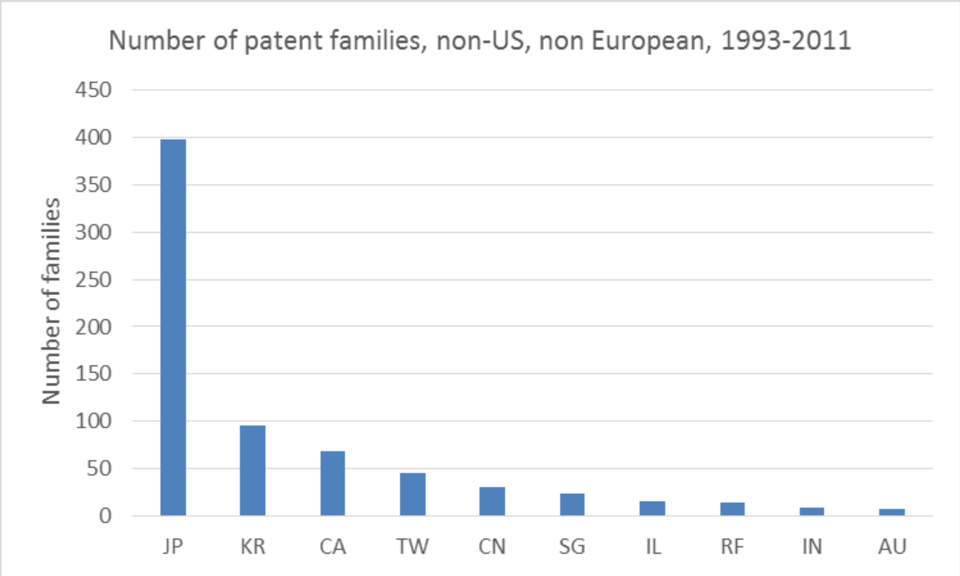


Figure 7-4: Number of patent families for non-US and non-European countries, 1993-2011

GRANTED PATENTS

Applicants from the same EU and EFTA countries perform strongly in patents granted, namely those from the UK, DE and France, and also have more patents granted at the USPTO than at the EPO.

Table 7-5: Patents granted by country of applicant, 1993-2011

	Country of Applicant	No. of Patents Granted (1993-2011)	
		EPO	USPTO
1	US	460	56
2	JP	279	58
3	UK	62	25
4	KR	52	7
5	DE	45	30
6	FR	44	22
7	CA	30	5
8	TW	24	1
9	DK	10	7
10	CN	9	1
11	IL	9	2
12	SG	9	5
13	BE	9	2
14	IT	9	8
15	NL	9	5

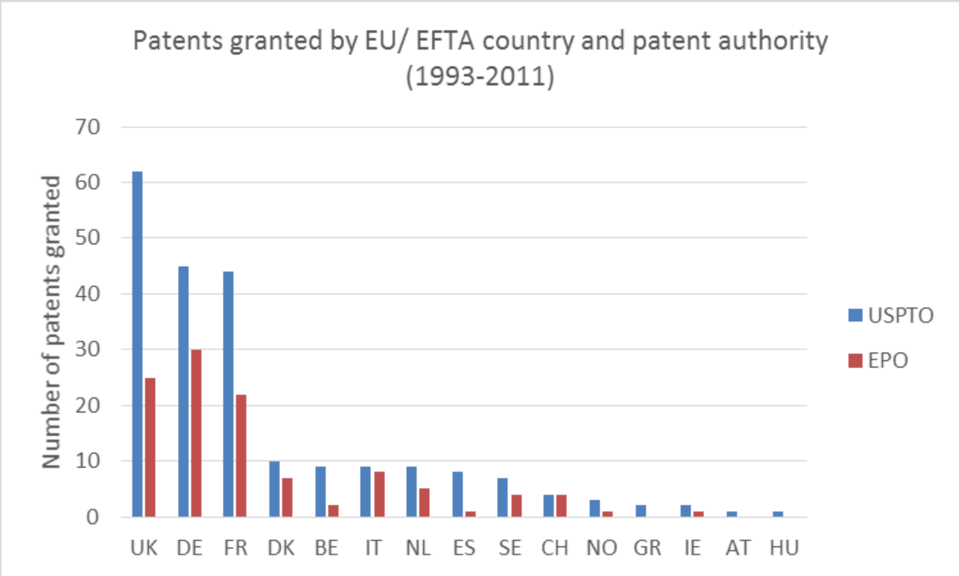


Figure 7-5: Patents granted to EU/EFTA applicants, by patent authority, 1993-2011

When considering the country of applicant and the country of inventor as seen in patent family data, it is clear that inventions are most often patented in the country in which they are invented (see table below). However, it is not uncommon to have inventions that are patented outside of the country in which they originate. In addition, inventions from inventors in the US are patented elsewhere and patent applications in the US may originate from work done elsewhere.

Table 7-6: Country of applicant and country of inventor table for cross-comparison

APPL	US	JP	UK	CA	DE	FR	KR	NL	SG	IT	SE	CN
INV												
US	758	18	27	16	17	17	12	9	4	7	6	6
JP	26	369	21	1	3	2	4	0	1	0	0	1
UK	24	6	111	4	8	3	0	1	2	1	3	0
CA	17	1	3	65	8	3	1	0	0	0	0	2
DE	16	2	6	8	132	1	0	6	1	5	0	2
FR	16	1	2	3	2	86	0	3	0	1	0	1
KR	13	4	0	0	0	0	94	0	0	0	0	3
NL	11	0	0	0	8	3	0	27	0	1	1	0
SG	11	1	2	0	1	0	0	0	14	0	0	0
IT	7	0	1	0	4	1	0	1	0	26	0	0
SE	7	0	0	0	0	0	0	1	0	0	18	0
CN	6	1	0	1	2	1	3	0	0	0	0	30

7.5 Patenting activity by organisation type

7.5.1 Universities and public research organisations

PATENT APPLICATIONS

Of the top ten universities and public research organisations (PROs) with the highest number of patent families (with percentages for PCT, US and EP applications), just one is in the EU28 (CNRS, France) and six are in the US. Japan (2) and Korea make up the remainder of the table. Seven of the top ten are universities, three (including the CNRS) being public research organisations.

Table 7-7: Number of patent families for top ten universities and PROs, 1993-2011

	Country	Organisation	No. of Patent families	PCT	US	EP
1	US	MIT	45	91%	93%	16%
2	US	University of California	45	64%	89%	24%
3	FR	CNRS	25	84%	60%	68%
4	JP	Kyoto University	25	72%	88%	32%
5	US	California Institute of Technology (Cal Tech)	18	61%	83%	17%
6	US	Princeton University	16	88%	75%	75%
7	US	University of Michigan	15	87%	73%	73%
8	US	Harvard College	14	79%	71%	0%
9	KR	Elect & Telecommunications Res Inst	13	8%	85%	8%
10	JP	Japanese Science & Technology Agency	13	54%	85%	69%

The table below shows the top 10 performing universities and PROs for patent families in EU28/EFTA countries. French organisations perform strongly (three of the top ten organisations in the table), as do German organisations (three of the top ten but with lower patent numbers).

Table 7-8: Number of patent families for top ten EU&EFTA universities and PROs, 1993-2011

World Rank	Country	Organisation	No. of Patent families	PCT	US	EP
3	FR	CNRS	25	84%	60%	68%
11	FR	CEA	13	54%	62%	46%
13	DE	Fraunhofer Gesellschaft	10	50%	10%	0%
14	BE	IMEC[228]	10	40%	90%	70%
23	UK	University of Glasgow	7	86%	29%	57%
26	ES	Universidad Politecnica de Valencia	6	100%	17%	50%
44	FR	CSIC	5	100%	0%	40%
54	BE	KU Leuven	5	40%	40%	80%
56	FR	Universite Paris Sud	4	100%	0%	0%
71	DE	Max Planck Gesellschaft	3	67%	0%	0%

GRANTED PATENTS

Of the top 15 universities and research organisations, two are from the EU28/EFTA countries, both from France (CNRS and CEA) as shown in the table below which is ranked by the highest number of US patents granted between 1993 and 2011. Seven of the organisations are from the US.

[228] Interuniversitair Micro-Elekctronica Centrum Vzw

Table 7-9: Universities and PROs granted patents, ranked by USPTO patent numbers, 1993-2011 (Top fifteen)

Rank	Country	Organisation	EP	US
1	US	MIT	2	39
2	US	University of California	2	22
3	JP	Kyoto University	1	20
4	US	California Institute of Technology (Cal Tech)	1	13
5	US	Princeton University	2	12
6	KR	Elect & Telecommunications Res Inst	1	10
7	JP	JP Science & Tech Agency	5	9
8	US	Stanford University	0	8
9	US	University of Illinois	0	8
10	US	University of Delaware	0	8
11	FR	CEA	2	7
12	US	University of Michigan	1	7
13	US	Northwestern University	0	7
14	US	Wisconsin Alumni Research Foundation	0	7
15	FR	CNRS	6	6

Ranking by EP patents, the top 15 universities and research organisations include four from the EU28/EFTA countries, two from France (CNRS and CEA), one from Germany (Fraunhofer) and one from the UK (University of Glasgow) as shown in the table below.

Table 7-10: Universities and PROs granted patents, top fifteen ranked by EPO patent numbers, 1993-2011

Rank	Country	Organisation	EP	US
1	FR	CNRS	6	6
2	JP	Japan Science & Tech Agency	5	9
3	JP	Kyoto University	3	2
4	DE	Fraunhofer Gesellschaft	3	1
5	US	Wake Forest University	3	1
6	US	Massachusetts Institute of Technology (MIT)	2	39
7	US	University of California	2	22
8	US	Princeton University	2	12
9	FR	CEA	2	7
10	CH	Ecole Polytechnique Federale De Lausanne (EPFL)	2	2
11	UK	University of Glasgow	2	2
12	JP	Kyoto University	1	20
13	US	California Institute of Technology (Cal Tech)	1	13
14	KR	Elect & Telecommunications Res Inst	1	10
15	US	University of Michigan	1	7

7.5.2 Activity of companies

PATENT APPLICATIONS

Of the top ten companies with the highest number of patent families (with percentages for PCT, US and EP applications), six are in Japan, two in the US, one in Korea and one in Germany (Osram). It should be noted that some may be holding companies rather than research companies or manufacturers.

Table 7-11: Number of patent families for top ten companies, 1993-2011

	Country	Company	No. of Patent families	PCT	US	EP
1	JP	Canon KK	62	26%	98%	34%
2	KR	Samsung Elect Co Ltd	32	6%	94%	44%
3	US	Hewlett Packard Dev Co LP	31	68%	81%	45%
4	JP	NEC Corp	29	69%	62%	17%
5	**DE**	Osram Opto Semiconductors GmbH	20	55%	85%	70%
6	JP	KK Toshiba	20	15%	85%	15%
7	JP	Hitachii Ltd	18	28%	72%	11%
8	JP	TDK Corp	17	65%	88%	47%
9	JP	Matsushita Elect Ind. Co Ltd	16	19%	94%	31%
10	US	Corning Inc.	16	88%	38%	63%

In the top ten companies for patent applications in EU28 and EFTA countries, four are from Germany, three from the UK and one each from the Netherlands, France and Denmark.

Table 7-12: Number of patent families for top ten companies EU28 & EFTA, 1993-2011

	Country	Company	No. of Patent Families	PCT	US	EP
1	DE	Osram Opto Semiconductors GmbH	20	55%	85%	70%
2	NL	Kon Philips Elects NV	16	88%	44%	100%
3	FR	Thales	13	54%	54%	92%
4	UK	Mesophotonics Ltd	11	91%	82%	64%
5	DE	Infineon Tech Ag	9	22%	44%	44%
6	DE	Siemens Ag	9	78%	22%	22%
7	DK	Crystal Fibre As	8	38%	63%	50%
8	UK	BTG Int. Ltd	7	86%	29%	57%
9	UK	Toshiba Research Europe Ltd	7	29%	0%	0%
10	DE	Deutsche Telekom AG	6	100%	33%	83%

GRANTED PATENTS

The top ten companies that have been granted patents by the EPO and/or USPTO are shown in the tables below[229]. The first table shows the top ten when the figures are sorted to obtain the highest number of EPO patents and the second shows the top ten when they are sorted for USPTO patents. When ranking by number of EPO patents, four of the companies are from Japan, three from the US and one each from Germany (Deutsche Telekom), Korea and France (Thales). When ranking by number of US patents, seven of them being in Japan, two in the US and one in Korea, none from the EU28 and EFTA.

[229] This data does not take account of there being multiple offices of one company. Where the name differs in the database, the companies are taken as being different.

Table 7-13: Companies that have been granted patents, ranked by EPO patents, 1993-2011

	Country	Company	USPTO	EPO
1	JP	Canon KK	54	14
2	US	Agilent Tech Inc	13	6
3	JP	Sumitomo Elect Ind Ltd	10	6
4	US	Lucent Tech Inc	10	5
5	DE	Deutsche Telekom AG	2	5
6	KR	Samsung Elect Co Ltd	17	4
7	JP	NEC Corp	14	4
8	FR	Thales	5	4
9	US	Hewlett Packard Dev Co LP	25	3
10	JP	TDK Corp	15	3

Table 7-14: Companies that have been granted patents, ranked by USPTO patents, 1993-2011

	Country	Company	US	EP
1	JP	Canon KK	54	14
2	US	Hewlett Packard Dev Co LP	25	3
3	KR	Samsung Elect Co Ltd	17	4
4	JP	TDK Corp	15	3
5	JP	KK Toshiba	14	3
6	JP	Matsushita Elect Ind. Co Ltd	14	2
7	JP	NEC Corp	14	4
8	JP	Hitachi Ltd	13	1
9	US	Agilent Tech Inc.	13	6
10	JP	Sumitomo Elect Ind. Ltd	10	6

The strength of Japanese companies in photonics and electronics is reflected in their domination of the patenting tables in nanotechnology/photonics.

The next section looks at the photonics industry including products with nanotechnology/photonics and global markets and trends.

8 INDUSTRY, PRODUCTS AND MARKETS IN NANOTECHNOLOGY AND PHOTONICS

8.1 Overview of the photonics industry

8.1.1 Introduction

In a report[230] from 2011, it was estimated that photonics impacts around 10% of the European economy as a contribution to the value of end products or services, enhancing the productivity of the manufacturing process or the functionality of the end device. The economic impact of photonics can come from the industry making photonics components and sub-systems (e.g. lasers, LEDs, screens and optical devices); from the industry enabled by photonics (e.g. automotive, telecommunications, lighting and medical industries all use photonics in their products and/or in the manufacture of their products); and in the end use in consumer markets ranging from food to aerospace. The report predicted significant growth in photonics in the future, most strongly in the following areas of the economy:

- Construction (photovoltaic and lighting technologies);
- Retail (displays and lighting);
- Transport (scanning, imaging and lighting); and
- Medical and health-care (all photonics technologies).

8.1.2 Revenue, employment and markets for photonics in Europe

A report for industry on the European Photonics Ecosystem[231] related that, in 2012:

- Revenue in Europe from photonics was EUR 65.8 billion (slightly higher than the figure above, taking into account a 10% growth rate); and
- Employment in photonics in Europe was 377,000 people, an additional 60,000 being needed by 2015.

Table 8-1: Types of photonic systems, photonic function and production

Type of photonic system	Photonic function	Production (billion EUR)
Sensing and imaging	Acquire information	28.9
Communication	Transmit information	7.2
Screens, displays, etc.	Deliver information	3.5
LED, OLED, lamp systems	Provide light	12.5
Photovoltaic systems[232]	Provide energy	4.3
Laser and production systems	Manufacture	9.4

European companies fall mainly into three categories: components (46%); systems and sub-systems (39%); and materials and manufacturing equipment (10%). Photonics-related companies in Europe include large companies such as Barco (projection and display)[233] and TE connectivity[234] and smaller ones that use photonics for sorting machines for food (no stones), printing using LEDs to control the ink (high-resolution large flyers).

There are two main databases including photonics companies. The Photonics21 database includes 1,951 European companies from the EU28 plus Norway, Switzerland, Israel, Liechtenstein, and Turkey. Company distribution for photonics by EU country (plus Switzerland), from the Photonics21 database, is shown in the figure (top fifteen countries only). Almost 30% of companies are based in Germany and 15% in France, closely followed by the UK. This is data on the membership of the ETP.

[230] "The Leverage Effects of Photonics Technologies: the European Perspective", A Study for EC DG Information Society and Media under SMART 2009/006 (2011), lead consultant TNO.
[231] Photonics Ecosystem in Europe, EPIC (the European Photonics Industry Consortium) and TEMATYS consultants, 2013. Report based on a survey of 447 organisations (49% manufacturers, 30% R&D and university, 14% engineering and consultancy) mainly in Germany, Finland, France, the UK and Spain.
[232] Only PV modules are included.
[233] http://www.barco.com/en/
[234] http://www.te.com/en/home.html#3

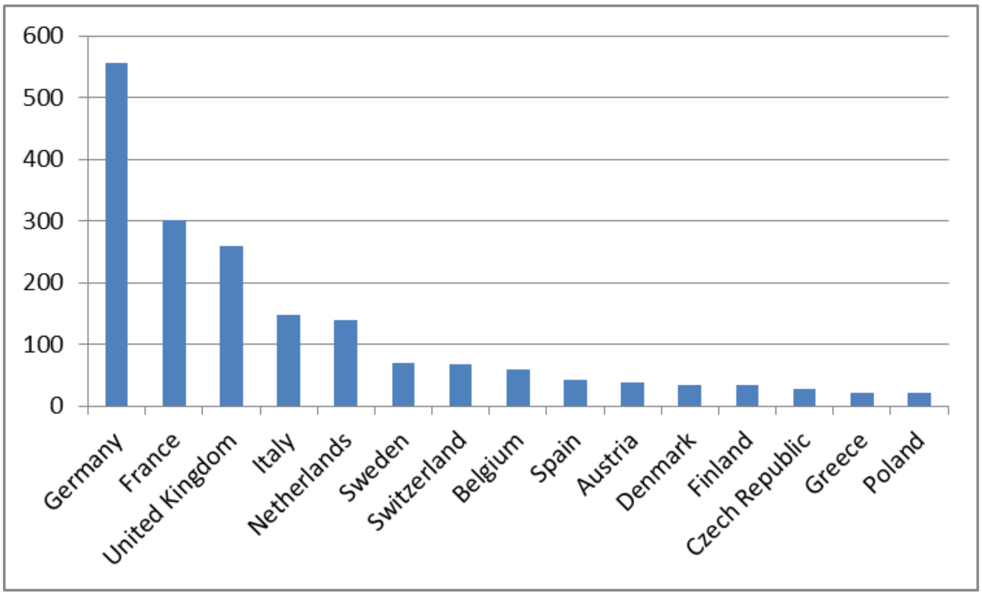


Figure 8-1: Overview of company distribution in Photonics21 database (top 15 countries)

Source: Adapted from: http://www.photonics21.org (organisation list) 9 June 2015

Another database is managed by EPIC, the European Photonics Industry Consortium. This database was constructed by EPIC and Tematys for their 2014 report on the Photonics Ecosystem in Europe. The most recent update is from September 2013. It includes 4,168 companies in Europe, including some companies in Russia, Ukraine, Armenia, Kazakhstan, and UAE. Again, Germany has the largest share, but followed closely by the UK. Together these countries have a share of 58%. France, the Netherlands and Italy follow at distance.

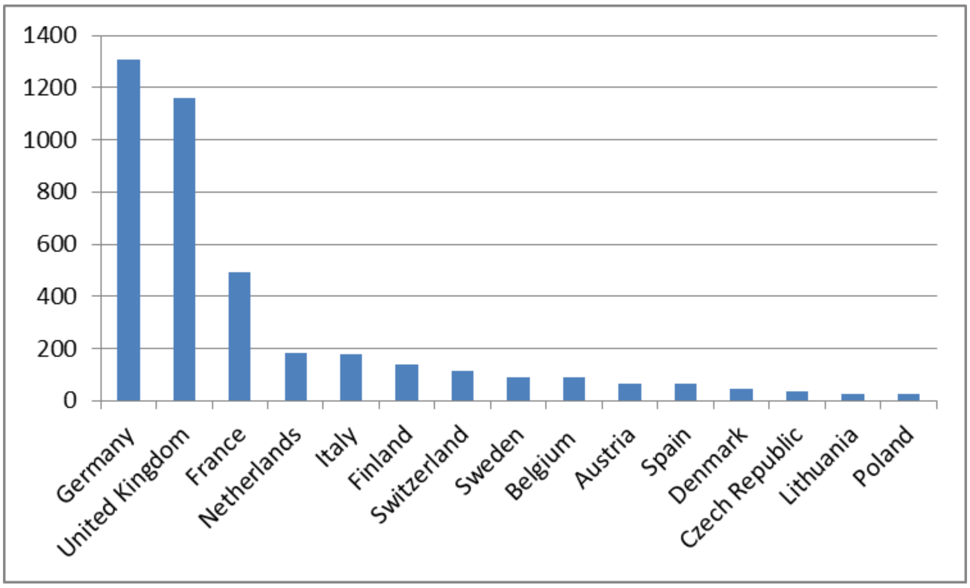


Figure 8-2: Overview of company distribution in EPIC database (top 15 countries)

Source: Adapted from: http://www.epic-assoc.com/database/ 9 June 2015

The photonics industry includes a relative high proportion of very small companies (60%), but also a significant number of multinational companies have their main office in Europe:

- Small companies (<20 employees) represented 60% of European photonics companies, 6% of employment (with 15% of the expected employment growth);
- Medium-sized companies (20-500 employees) were the most significant employers with 40% of the employees (55% of anticipated growth) and 36% of companies;
- Large companies (>500 employees) provided a stable base with 4% of companies, 53% of

total employment and 30% of expected employment growth; and
- 58% of companies specialised in photonics (>80% of revenue from photonics) but photonics is a small part of their revenue for 24% of large and medium-sized companies.

In terms of markets, as reported[235] in 2012, the European photonics industry typically sold as follows:

- 13% into manufacturing;
- 10% into laboratory equipment;
- 9% into health-care and biomedical;
- 7% into life sciences;
- 6% each into automotive and defence;
- 5% each into energy, lighting, consumer electronics and communications; and
- 29% into other markets.

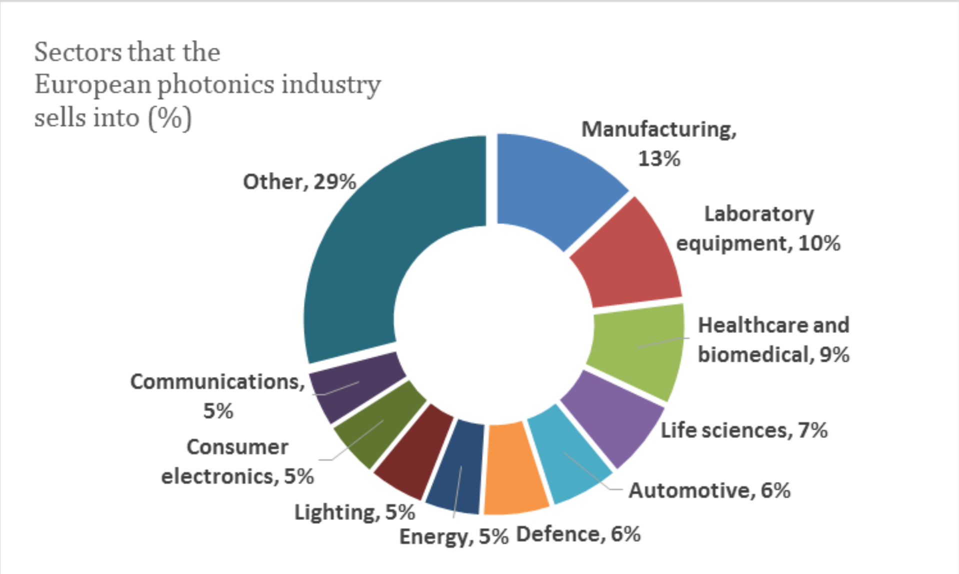


Figure 8-3: European photonics industry sales by sector, 2012

As a whole, more than 50% of European sales are to markets outside of Europe, mainly in Asia and North America.

Europe's share in the global market amounts to 18%. World market share for key European photonics industry sectors is estimated by Photonics21[236] as:

- Production technology: 55 %;
- Optical components and systems: 40 %;
- Image processing and metrology: 40 %; and
- Medical technology and life sciences: 30 %

8.2 Overview of the nanotechnology photonics industry

The Nanophotonics Industry Association[237] identified (2011) ten nanotechnology photonics research areas expected to have disruptive impact on the photonics industry by 2021:

- nanoscale quantum computing;
- all optical routing (for signal processing and fully optical networks);
- plasmonics for enhanced magnetic data storage;
- diagnosis, therapy and drug delivery using light;
- nanoscale imaging;
- chemical and biological molecular-scale sensors;
- nano-tagging (for food safety, anti-counterfeiting and medical diagnostics);

[235] Photonics Ecosystem in Europe, EPIC (the European Photonics Industry Consortium) and TEMATYS consultants, 2013.
[236] http://ec.europa.eu/research/industrial_technologies/pdf/photonics-ppp-roadmap_en.pdf
[237] www.nanophotonicseurope.org

- light distribution at the nanoscale (to optimise light emission and absorption);
- new processing techniques for prototyping; and
- nanophotonic materials with tailored optical properties.

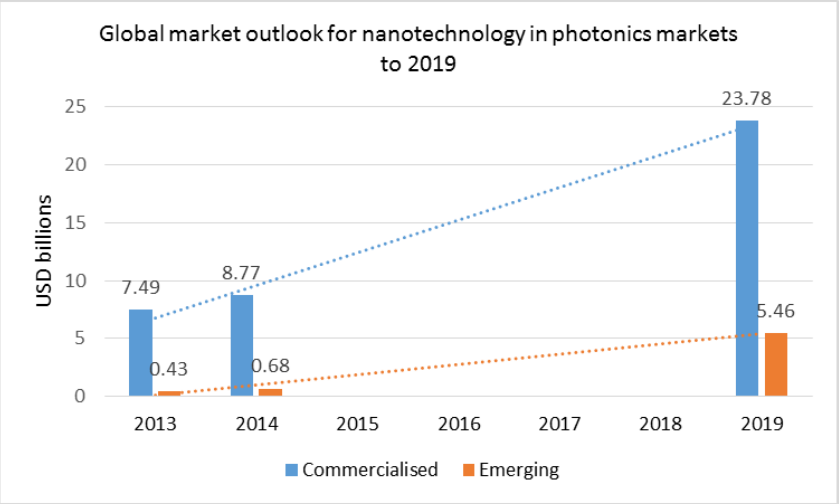
Nanophotonics technology[238] is expected to enter the mainstream market because of the low weight of the nanomaterials in development, their high thermal stability, increased power efficiency and potentially long working life. This in turn could result in a significant increase in the number of applications in near-field optics, holographic memory and optical amplifiers, as well as technologies to improve the quality of the optical fibres that are replacing copper wires in some applications. Among the major challenges facing manufacturers of nanotechnology photonics products are the current high cost of integrating nanotechnology with photonic equipment and components, difficulty in justifying price increases for performance, the need for an experienced and knowledgeable labour force, and the extensive R&D costs for bringing in new products.

The sections that follow will consider products for nanotechnology/photonics and will continue to review markets by looking at global markets and trends.

8.3 Products and markets for photonics and nanotechnology

8.3.1 Global markets and forecasts for photonics nanotechnology products

Global sales for nanotechnology products in the photonics sector were estimated to be USD 7.9 billion in 2013 and are forecast to be USD 29.2 billion in 2019, a compound annual growth rate (CAGR) of over 24%. The figure below shows the forecast growth in commercialised products (USD 23.8 billion in 2019) and the expected growth in emerging products (USD 5.5 billion in 2019). It is seen that much of the growth is expected to be driven by products which are already commercialised.

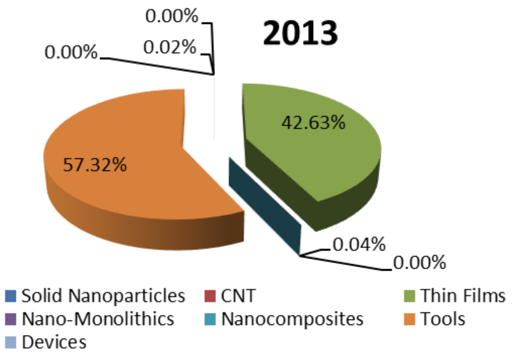


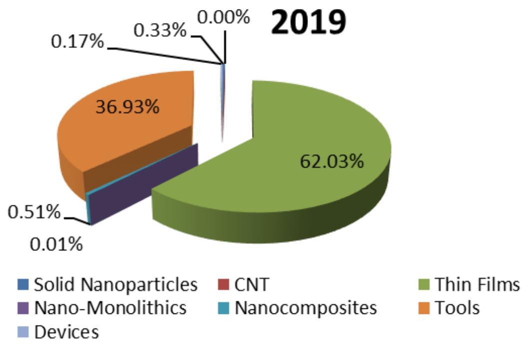
Source: BCC Research, 2014

Figure 8-4: Global market outlook for nanotechnology in photonics markets to 2019

A comparison of global sales estimates by type of nanomaterial shows that nanotools account for the largest share in 2013 with an expected decrease by 2019. In comparison, the share of thin films is expected to grow significantly in the same period. The main driver of this trend is the expected growth in the flat panel display market.

[238] Frost & Sullivan: 2015 Top Technologies in Microelectronics (Technical Insights), 2015; Frost & Sullivan: Advances in Photonic Materials (Technical Insights), 2014; Frost & Sullivan: Silicon Photonics (Technical Insights), 2010; Frost & Sullivan: Nanotech Alerts, 2000-2015; Nanophotonics Europe Association: Nanophotonics foresight report, 2012; Nanophotonics Europe Association: Nanophotonics: A forward look, 2012; Markets & Markets: Nanophotonics- Advanced Technologies and Global Market (2009 - 2014); Grand View Research: Nanophotonics Market Analysis.





Source: BCC Research, 2014

Figure 8-5: Global sales estimates for nanotechnology and photonics by material type, 2013 and 2019

The shares of solid nanoparticles, nanocomposites, nano-monolithics, nano tools, and devices are negligible in 2013 as well they are expected to be in 2019.

Nanotechnology is making inroads in photonics in the existing and growing markets of photovoltaics (PV or solar cells), light emitting diodes (LEDs), organic light emitting diodes (OLEDs) and near field optics.

In the section that follows, products and groups of products will be discussed. It explores the markets for nanotechnology in photonics, beginning in each case with the technology and products (with company examples) and concluding with market estimates and forecasts. The market data presented there is based mainly on reports by BCC Research[239]. Company snapshots and company case studies are included. In addition, where appropriate, information is presented on likely future products and markets. First there is an overview of the products.

8.3.2 Commercialised products for nanotechnology and photonics

8.3.2.1 Overview

The main uses of photonics are[240]:

- Scanning, sensing and imaging systems;
- Data transmission, storage, communication and networks;
- Screens and displays;
- Advanced lighting;
- Photonic energy systems; and
- Laser systems.

To date, over 150 photonics-related products using nanotechnology have been identified as being commercially available on the market. These are broken down by type in the figure below. The majority fall into the application areas of advanced lighting, screens and displays, and other optical applications, as well as electronics for the systems and networks mentioned above.

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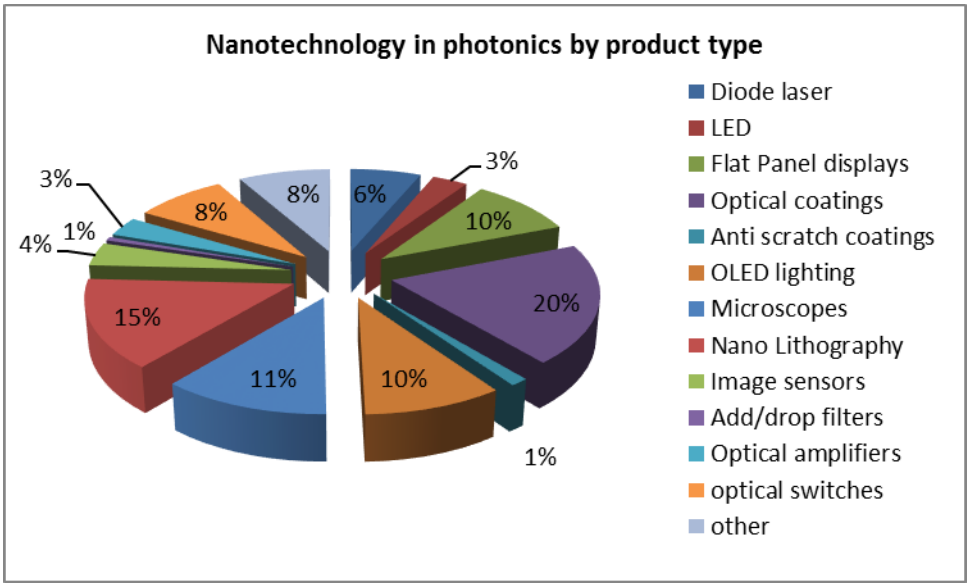
[239] It should be noted that market estimates and forecasts undertaken by different organisations are based on different assumptions and methodologies, sample a different set of expert opinions and use different models to arrive at the data they present. By using data from one organisation, and linking it to original NanoData work on products, the aim is to minimise the error between datasets. However, there is no evidence that these data are more correct than other data. In order to address this, future work of the NanoData project will involve stakeholder interviews and workshops having the goal of evaluating the data, working towards its validation.

[240] "The Leverage Effects of Photonics Technologies: the European Perspective", A Study for EC DG Information Society and Media under SMART 2009/006 (2011)



Source: JIIP, 2015

Figure 8-6: Nanotechnology in photonics by product type

Around one-fifth (21%) of those are in the area of optical coatings and anti-scratch coatings. Nano-lithography (15%) accounts for the second largest share amongst commercially-available products as shown in the figure above. Further shares worth mentioning are microscopes (11%) and flat panel displays (10%).

8.3.2.2 Products for photonics through nanotechnology by commercialised application market

The products and groups of products discussed in this section, with information about the technology as well as market estimates and forecasts. The list below identifies the product type and, in brackets, the type of nanotechnology (e.g. quantum dot, nano-tool):

- Laser diodes (quantum dots);
- Light-emitting diodes (LEDs) (nanophosphors, quantum dot films);
- Organic LEDs – flat panel displays (nanoparticles, thin films);
- Lens coatings (for spectacles and other applications) (nano-coatings);
- Optical recording media (nano-films);
- Optical fibre cladding (nano-coatings);
- Anti-scratch/ anti-stick coatings (nano-coatings);
- Organic LEDs – lighting (thin film);
- High-pressure discharge lamps (ceramic nanomaterials);
- Near-field optical microscopes (nanotools); and
- Advanced lithographic tools (nanotools).

In addition, the following emerging applications (again with the nanotechnology in brackets) are discussed:

- Flat-panel displays (quantum dots);
- Digital image sensors (quantum dots);
- Transparent conducting electrodes (carbon nanotubes, graphene);
- Super lenses (nanowires);
- Photonic add/drop filters (nanocomposites);
- Optical switches (quantum dots);
- Optical amplifiers (op amps) (quantum dots);
- Next generation nano-lithographic tools (nanoimprint, nanotools); and
- Holographic memory (spin waves).

Case studies and company snapshots are provided as examples.

A Laser diodes

A laser diode, also known as an injection laser or diode laser, is a semiconductor device that produces coherent radiation (in which the waves are all at the same frequency and phase) in the visible or infrared (IR) spectrum when current passes through it. They are used in optical fibre systems, compact disc (CD) players, laser printers, remote-control devices, and intrusion detection systems[241].

Albeit that quantum dot lasers are still at an early stage of commercialisation, some have introduced this technology already to the market and others are undertaking research and development:

- Zia Laser Inc. (Albuquerque, N.M., USA) was the first company to offer a commercial version of the quantum dot laser diode. (Zia ceased operations in 2006 before being acquired by Innolume GmbH (Dortmund, Germany))[242].
- IQD Laser Inc. was founded by Fujitsu and Mitsui Investment (Japan) to outsource R&D activities in quantum dot semiconductor crystallisation techniques and laser design processes[243]. Several other research institutes are also working on their own versions of the quantum dot laser[244].
- In 2009, Fujitsu announced what is reportedly the world's first quantum dot laser capable of 25 gigabits per second of data transmission[245].
- In 2011, researchers at University College of London and the London Centre for Nanotechnology demonstrated an electrically driven quantum dot laser grown directly on a silicon substrate (Si) with a wavelength (1300-nm) suitable for use in telecommunications[246].

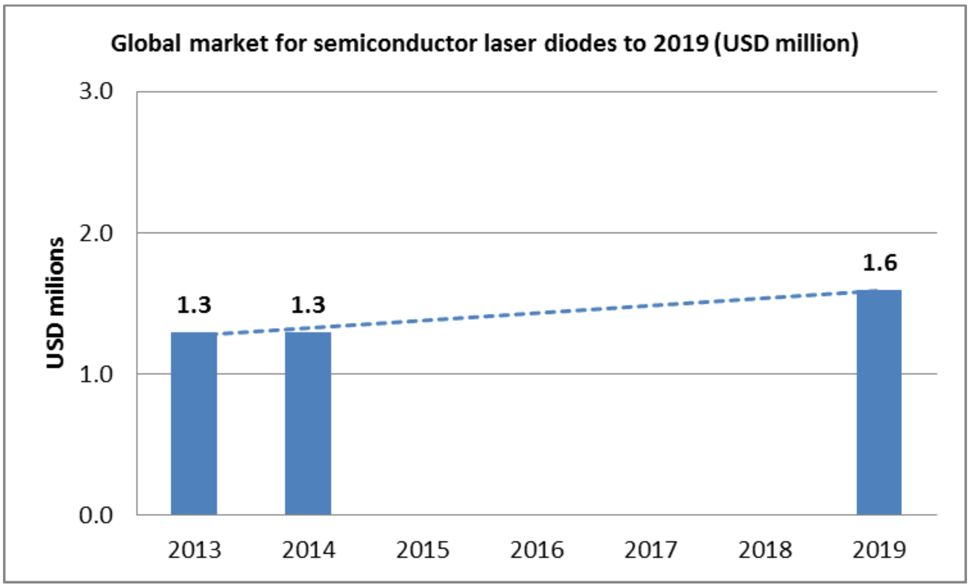
Company snapshot: Innolume

Innolume GmbH manufactures laser diodes. The company's products include laser diode drivers; single-mode laser diodes; broad-area laser diodes; comb-lasers; distributed feedback and distributed bragg reflector lasers; gain-chips; gain-modules; semiconductor optical amplifiers; super luminescent diodes; resonant cavity light emitting diodes and light emitting diodes; and quantum dot and quantum well wafers for optoelectronic applications. It provides its products for use in Raman amplification, optical interconnect, and medical and industrial applications. Innolume GmbH was formerly known as NL-Nanosemiconductor GmbH and changed its name to Innolume GmbH in January 2007. The company was incorporated in 2002 and is based in Dortmund, Germany. Innolume's revenue as of 2013 was EUR 1.62 million.

Market data and forecasts

Sales of quantum dots for use in semiconductor lasers are currently limited. However, quantum dot-based diode lasers show considerable long-term promise, particularly in the optical telecommunications market. Although data on global consumption of semiconductor laser diodes are hard to obtain, BCC Research estimated the figure for 2013 at USD 1.3 million. The total global market for diode lasers was worth about USD 4.3 billion in 2013 and is projected to grow at a CAGR of 2% over the next five years. It is forecast that the market for quantum dot laser diodes will grow about twice as fast as the overall diode laser market (i.e. at an average annual rate of 4.2%). Due to the impracticality of separating the cost of the quantum dot laser diodes from the rest of the solid-state laser diode, the figures in the graph below reflect the cost of the entire semiconductor diode market[247].

[241] http://whatis.techtarget.com/definition/laser-diode-injection-laser-or-diode-laser
[242] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.35
[243] http://www.qdlaser.com/?page_id=47
[244] http://www.laserfocusworld.com/articles/2011/06/quantum-dots-address-a-range-of-new-applications.html
[245] Ibid
[246] http://www.eurekalert.org/pub_releases/2011-06/ucl-ugf061111.php
[247] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.130



Source: BCC Research

Figure 8-7: Global market for semiconductor laser diodes

B Light-emitting diodes (LEDs)

LEDs substitute for light bulbs in an increasing number of lighting applications. Unlike conventional incandescent lamps, which need to convert the electricity into thermal energy first and then to light, LED illumination is achieved when a semiconductor crystal is activated so that it directly produces visible light in a desired wavelength range[248]. Nevertheless, a low-cost, mass-market white-light diode with the potential to replace conventional incandescent bulbs and fluorescent tubes seems currently still out of reach for LED researchers and manufacturers.

One possible solution is the use of nanophosphors (i.e. semiconducting nanoparticles that emit light under excitation) in the form of white LEDs. If the phosphor particles are smaller than 20 nm in diameter scattering of light waves is reduced and thus greater optical and energy efficiency is achieved[249]. Some of the activities in this area include:

- Phosphor Technology Ltd. (UK) has developed and manufactured phosphors for blue to white LED conversion for several years. It is also working on phosphors for CRTs, FEDs, plasma display panels, X-Ray applications, IR and UV detection, scintillator applications and laser detection[250].
- Another UK company developing nanophosphor for LED applications is Forge Europa which received national funding of GBP 0.63 million from Innovate UK for 2005-2008 for its project Nanophosphors for Displays and Lighting[251] [252].
- QD Vision (USA) has developed a quantum dot film coating for the lens of LED lamps to give the light emitted a warmer, more yellow glow through photoluminescence[253]. Quantum dots (QDs) absorb one wavelength of light and emit another, the emission being determined by the size of the quantum dot, making the light tunable by varying the size of the QD[254]. QD Vision and Nexxus Lighting of Charlotte, N.C., announced in 2010 the first commercially available QLED lightbulb with an industry-leading 60-lumens per Watt (lm/W)[255] white-light output[256].
- The company Nanosys uses its "quantum-dot-enhancement film" (QDEF) to tune the spectrum from LEDs to be more like the white light the human eye is used to. It does this by passing the LED light through a transparent film containing quantum dots, which absorb and re-emit some

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248 LED inside: Advantages and Weaknesses of LED Application, December.20, 2007
249 Zachau M, Konrad A (2004), Nanomaterials for Lighting, Solid State Phenomena Vols. 99-100 (2004): 13
250 Mills A (2005), Phosphors development for LED lighting, III-Vs Review Volume 18, Issue 3, April 2005: 33
251 http://news.bbc.co.uk/2/hi/science/nature/3591192.stm
252 http://gtr.rcuk.ac.uk/projects?ref=150017
253 BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.40
254 PHOTONICS Spectra: Quantum Dots Warm Up LED Lighting. October 2011.
255 Lumens per Watt (luminous flux per electric power unit) lm/W
256 Ibid

of the light[257]. The QDEF is composed of proprietary quantum dot phosphors from Nanosys, which convert blue light from a standard gallium nitride (GaN) LED into different wavelengths based on their size. Blending together a mix of dot colours allows LCD manufacturers to accurately match the LED backlight to the LCD colour filters to achieve the best possible colour and efficiency performance. Nanosys has begun shipping QDEF material to original equipment manufacturers such as ASUS (Taiwan) and VP Dynamics Labs (San Diego, Calif.)[258].

Company snapshot: Nanosys

Nanosys is a nanotechnology company that designs products based on "architected materials," materials purpose-engineered for a given manufacturing process. This approach is currently being applied to multiple industries, including LED backlighting, LED general lighting, power (batteries and fuel cells), medical applications, and specialised nano-surface coatings.

Founded in 2001, Nanosys is headquartered in Silicon Valley, California, US, where it operates the world's largest quantum dot nanomaterials fabrication facility (Fab) with manufacturing capacity of over 25 tons of quantum dot materials per year. By 2011, the invested capital in the company was USD 130 million and the business had generated more than USD 75 million in revenue.

The business model of Nanosys consists of two elements: sales of Quantum Dot Concentrate™ material and technology licensing of component designs to industrial supply chain partners. For instance, their Quantum Dot Enhancement Film (QDEF®) is a key component of Ultra High Definition (UHD) televisions.

The Company has one of the largest quantum dot patents portfolios with over 300 (issued and pending) patents worldwide which cover all processes from fundamentals of quantum dot construction to component and manufacturing designs. This portfolio has been created thanks to collaborations between Nanosys and research and education organisations such as Massachusetts Institute of Technology (MIT, US), Lawrence Berkeley National Labs (US) and the Hebrew University (IL), as well as industry collaborations with companies like Philips-Lumileds[259] and Life Technologies. Amongst their partners for tablets and televisions are companies such as 3M, Samsung, Sharp and LG.

MARKET DATA AND FORECASTS

The first commercial LED products incorporating nanoparticles were Nexxus Lighting's quantum dot-coated LED ceiling lamp fixtures, which began arriving on the market in small quantities in 2010. High-brightness LEDs are a potential market for both quantum dots and rare earth nanophosphors. It is forecast that the market for quantum dots[260] and for rare-earth nanophosphors[261] used in LED applications could both reach at least USD 34 million each by 2019.

Table 8-2: Global market for nanoparticles in LED production

Global Market for Nanoparticles in LED Production	2019 (USD million)
Quantum dots	34.0
Rare earth nanophosphors	34.0
Total nanoparticles	68.0

Source: BCC Research

[257] The Economist: Dotting the eyes - Quantum-dot displays, Jun 16th 2011
[258] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.40
[259] http://www.lumileds.com/ Lumileds was set up in 1999 as a joint venture between Philips and Agilent Technologies
[260] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.135
[261] BCC Research report NAN036B

C ORGANIC LEDS – FLAT PANEL DISPLAYS

Organic light-emitting diodes (OLEDs) are light-emitting diodes (LEDs) containing a film of organic compound that emits light in response to an electric current. The film, an organic semiconductor layer, is situated between two electrodes, at least one which is usually transparent. OLEDs are used to create digital displays in devices such as television screens, computer monitors and portable systems such as mobile phones and handheld game consoles[262]. Nanotechnology can be used to increase the brightness and efficiency of OLEDs.

OLEDs are lightweight, flexible, transparent and can be colour tuned, making them an ideal light source for devices. They do not require backlighting and have a wide viewing angle and a low operating voltage (less than 5V). They emit light throughout the visible range (achieved by modifying the chemical structure of material) and are suitable for flexible displays. They have reduced production costs over traditional LEDs[263]. Their main limitation is that their materials degenerate quite rapidly, thereby limiting their use[264].

The two main classes of OLED devices are those made with small organic molecules and those made with organic polymers[265]. Most OLED devices on the market today use the small molecule technology pioneered by Kodak. A typical double-hetero-structure small-molecule OLED consists of three organic layers sandwiched between electrodes. The organic layers adjacent to cathode and anode are the electron transport layer (ETL) and the hole transport layer (HTL), respectively. The emissive layer (EML) usually consists of light-emitting dyes or dopants dispersed in a host material (often that same as either the HTL or the ETL material)[266]. Small molecule OLEDs are most suitable for the relatively small (i.e. less than 15-inch, 38 cm) displays found in shavers, cellphones and digital cameras. Sony introduced the first commercial OLED TV, the 11-inch XEL-1, in late 2007 using the small molecule technology. By 2014, both Samsung and LG were offering 55-inch small molecule OLED displays, with larger displays to follow[267].

Polymer OLED (P-OLED) display technology is seen as the driver of future growth in the OLED market given the trend towards larger television screens. Polymer OLED materials are readily soluble using ink solvents, resulting in materials suitable for wet printing processes such as like inkjet, die-coating, etc. which are considered to be appropriate for the fabrication of large sized OLED devices[268]. These processes are very suitable for nanoinks to create thin films. P-OLEDs have relatively simple architectures, with the light-emitting polymer (LEP) layer combining host, emitter and charge transport functions in a single solution-processed layer of the device. Materials most commonly used in LEPs are poly(phenylene vinylene) (PPV) and polyfluorene (PFO) polymers[269].

UK-based Cambridge Display Technology (CDT) is the company that holds the basic patents for polymer OLED technologies. The company has licensed its technology to several companies, including Philips, Seiko Epson, Osram, Dupont and Delta Optoelectronics. Sumitomo and CDT are still developing P-OLED materials and panels, and are mostly targeting the low-cost display and lighting markets[270].

However, the shift to polymer OLED displays suffered a setback in 2014 when Panasonic, the only major display manufacturer that had been developing polymer OLED displays, announced that it was exiting the OLED business. Panasonic and its development partner, Sony, reportedly had found it difficult to reduce the high production costs associated with OLED displays through mass production, and the firms are now planning to shift their focus toward top-tier LCD televisions, such as 4K ultrahigh-resolution models[271].

[262] Shire A, et al. (2015), A Review Paper on: Organic Light Emitting Diode over Conventional Led, International Journal of Advanced Research in Computer Science and Software Engineering, Volume 5, Issue 1, January 2015: 178

[263] Karzazi J (2014), Organic Light Emitting Diodes: Devices and applications, J. Mater. Environ. Sci. 5 (1) (2014)

[264] http://www.talkoled.com/oled-tv/

[265] Ibid

[266] http://www.sigmaaldrich.com/materials-science

[267] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.61

[268] Sekine C, et al. (2014), Recent progress of high performance polymer OLED and OPV materials for organic printed electronics, Science and Technology of Advanced Materials, 15 (2014): 2

[269] http://www.sigmaaldrich.com/materials-science

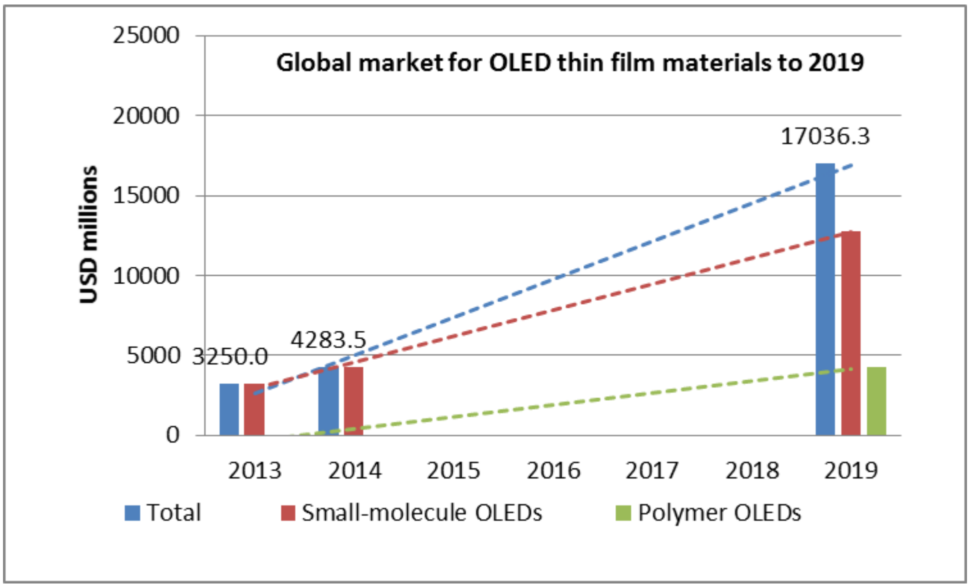
[270] http://www.oled-info.com/p-oled

[271] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.61

MARKET DATA AND FORECASTS

OLED panel shipments were worth USD 6.5 billion in 2013. Most of these panels were small-molecule displays used in cell-phones and small appliances. BCC Research estimated the cost of the OLED thin film materials used in these displays at about 50% of their total cost, or USD 3.3 billion in 2013. BCC Research projects that shipments of small-molecule OLED panels will reach about USD 8.6 billion in 2014 and USD 25.6 billion in 2019. As a result, the market for small-molecule OLED materials should grow to almost USD 4.3 billion in 2014 and USD 12.8 billion in 2018[272].

Sales of polymer OLEDs were negligible in 2013 and 2014. As discussed earlier, manufacturing problems so far have stood in the way of large-scale commercial production of polymer OLEDs. However, BCC Research expects that these problems will be solved, and the polymer OLEDs will capture 25% of the market, worth USD 8.5 billion, by 2019. On this basis, sales of polymer OLED thin film materials should approach USD 4.3 billion by 2019[273].



Source: BCC Research, 2014

Figure 8-8: Global market for OLED thin film materials

Case study: Beneq Oy

Beneq was established in May 2005 in Vantaa (Finland) as a management buy-out (MBO) spin-out from Nextrom (ex. Nokia-Maillefer). Beneq's competence background (under Nextrom) is in the fibre optics industry. The company designs and manufactures coating equipment based on nanotechnology. It is a leading supplier of production and research equipment for thin film ALD and aerosol coatings, as well as the world's premier manufacturer of the thin film electroluminescent (TFEL) displays that are produced in its Lumineq sub-unit.

In 2007 - already two years after its foundation - Beneq Oy was successful participating in FP6, winning a project on novel, hetero-atomic boron, nitrogen and carbon nanotubes (BNC Tubes), with EC funding of EUR 52,000 and total cost of EUR 102,000.

The swift and dynamic growth of the company soon caught the eye of the public. In 2008, Beneq won the title of best young growth company in the Future Winners competition arranged by Helsingin Sanomat, the largest newspaper in Finland. In 2012, Beneq was awarded the Internationalisation Award by the President of the Republic of Finland.

Beneq was successful again in applying for EC FP7 funding and won three contracts. In 2012, it received EC funding of EUR 295,414 (the total cost of the project being EUR

[272] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.150
[273] Ibid

390,244.8) for a project on roll-to-roll manufacturing of high efficiency and low cost flexible CIGS[274] solar modules. In 2013 it won two contracts, one on process line implementation for applied surface nanotechnologies with an EC funding of EUR 1,076,370 (total cost EUR 1,548,360) and one on novel catalyst structures employing platinum at ultra-low and zero loadings for automotive MEAs[275] with EC funding of EUR 356,014 (total cost EUR 533,972).

Beneq has been very active in protecting its new technological knowledge. In its portfolio are currently 131 patents of which five are directly related to nanotechnology; among these are patents on the production of carbon nanotubes, gas vapour deposition, a method for structuring a vitreous surface, multilayer coatings, and a process for producing a solar cell substrate.

Venture capitalists also have shown strong faith in Beneq's future – the investors include Finnish Industry Investment Ltd and the Danish capital investment fund Via Venture Partners (together with 9 million euro in 2011) and the Russian government-owned investment company RusNano (EUR 25 million investment in 2012).

Beneq is also very active in developing new business fields by bringing in its proprietary knowledge into new strategic partnerships to serve promising markets: In 2013, Beneq and i-sft announced the start of a strategic joint development of a completely new display technology for very demanding applications. In 2014 Beneq and DSM partners have introduced a novel aerosol deposition technology for solar applications. Beneq will contribute its recently released nFOG™ aerosol coating technology while DSM will provide its unique KhepriCoat® AR[276] coating. The combination of these two technologies provides an AR coating solution that is ideal for applications that require a superior coating quality on solar glass.

Beneq's knowledge-driven business development that has been also been fuelled by EC funding has materialised in a significant growth in employment and turnover in recent years. Starting with 12 employees and a turnover of EUR 0.6 million in 2005, the company reached a EUR 24.1 million turnover in 2013. Employment has grown to 162 people in 2013 working in headquarters in Vantaa, in clean room facilities in Espoo (also in Finland) and in its sales offices in Germany, China and the US.

In recent years, the company has been moving from piloting to industrial production. As for 2015, Beneq plans to hold significant positions in markets worldwide: 90% of the market for ALD glass strengthening, 60 to 70% of c-Si passivation, 50% of CIGS buffer layers for solar panels and 45% of the OLED encapsulation market.

D Lens coatings (spectacles and other applications)

Nanotechnology-enabled optical coatings that are dust, water dirt and oil repellent and improve the refraction index of the lens are a very attractive addition to the polycarbonate lens materials that are very widely used in optics. While the polycarbonates are lightweight, they are more prone to scratching than glass lenses. Some of the activities in this area include:

- Nanofilm Ltd. (Valley View, Ohio) has sold protective coatings for ophthalmic lenses since 1989. These durable, permanent coatings are less than 10 nanometres thick and use self-assembling polymer nanoparticles that form a chemical bond with the lens at the molecular level. The process results in a durable, long-lasting nano-film that seals the lenses and repels dirt, dust and skin oils. Initially developed for ophthalmic lenses, nano-film optical coatings have expanded into other applications, including binoculars and cameras. Other emerging applications include automated teller machines, hand-held electronics and the touch-screen instruments in military aircraft[277].
- ZEISS PureCoat® PLUS by ZEISS (Jena, Germany) is a nanoparticle based anti-reflective technology that helps to reduce reflections to less than 1% of the light — compared with 7% to

[274] Copper indium gallium selenide
[275] Membrane electrode assembly
[276] AR coating: Antireflective or anti-reflection coating, a coating applied to the surface of lenses and other optical elements to reduce reflection and reduce light loss.
[277] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.62

13% for uncoated lenses[278].

- Nikon (Chiyoda, Japan) has developed a technology to form a coating with very low refractive index even in vacuum ultra-violet region (VUV, 200-150 nm wavelengths), and greatly improved the angular performance of antireflection coating. This ultra-low refractive index coating is called "Nano Particle Coating" because the size of the particles that compose this coating ranges from a few nanometres to just over 10 nanometres[279].
- SWC (SubWavelength structure Coating), developed by Canon, is a new type of technology that uses aluminium oxide (Al_2O_3) as the structural material of the coating in order to align countless wedge-shaped nanostructures only 220 nm high, less than the wavelength of visible light, on a lens surface. This nano-scale coating provides a smooth transition between the refractive indexes of glass and air, successfully eliminating the boundary between substantially different refractive indices. Reflected light can be limited to around 0.05%. Furthermore, it has displayed excellent reflection-prevention properties not seen in conventional coatings even for light with a particularly large angle of incidence. Currently, SWC is being used in a broad range of lenses, not only wide angle lenses, which have a large curvature factor, but also large-diametre super-telephoto lenses, greatly reducing the occurrence of flare and ghosting caused by reflected light near the edges of the lens[280].

Company snapshot: Nanofilm

Nanofilm, Ltd. is a subsidiary of PEN, Inc. one of the US's leading companies focused on developing and commercialising advanced-performance products enabled by nanotechnology. It develops nano-layer coatings, nano-based cleaners, and nano-composite products. Founded in Ohio, US in 1985, Nanofilm has created thin films, nanometres in thickness, during more than thirty years. Nanofilm's primary commercial products are based on its unique eye-wear lens cleaning, "best-in-class" de-fogging products and nanotechnology treatments that enhance glass and ceramic surfaces to provide special properties. Examples include enabling easy removal of fingerprints from touchscreens, making shower doors resistant to soap scum and dirt accumulation, stay-clean surface treatments for ceramic insulators, and scuff-resistant treatments for commercial dinnerware.

PEN Inc. (PENC) is a global leader in developing, commercialising and marketing enhanced-performance products enabled by nanotechnology. The company focuses on innovative and advanced product solutions in safety, health and sustainability.

Market data and forecasts

The sales of polymer-based nanoscale thin film coating materials for eyeglasses, binoculars and cameras has been estimated to be about USD 23 million in 2013, based on sales figures for Nanofilm Ltd. Future sales of nanoscale optical coatings will be determined by their ability to increase their penetration of the total eyeglass coating market, which, as shown in the table below, is slowly declining.

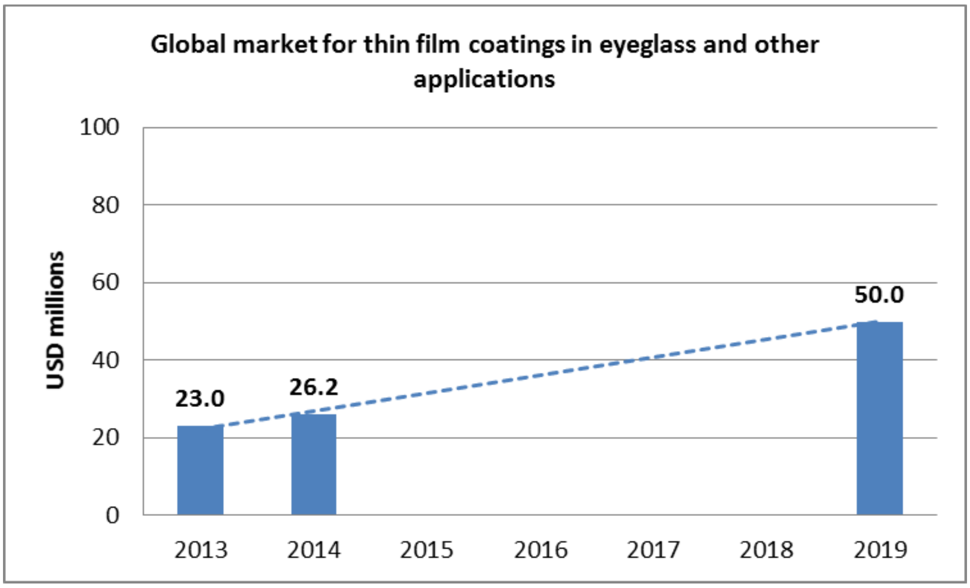
Table 8-3: Global eyeglass coating sales

	2013	2014	2019	CAGR 2014-2019
	USD million			%
Eyeglass Coating Sales	836	835	826	-0.2

Source: BCC Research

The share of the total eyeglass coatings market taken by nanostructured polymer coatings was a little under 3% in 2013 and is forecast to more than double to about 6% by 2019, as shown in the figure below.

278 http://www.zeiss.com/vision-care/en_us/products-services/coating-coloured-lenses/coatings/purecoat.html#details
279 http://nikon.com/about/technology/rd/core/material/nano_particle/index.htm
280 http://www.canon.com/technology/s_labo/light/003/03.html



Source: BCC Research

Figure 8-9: Global market for thin film coatings in eyeglass and other optical coatings

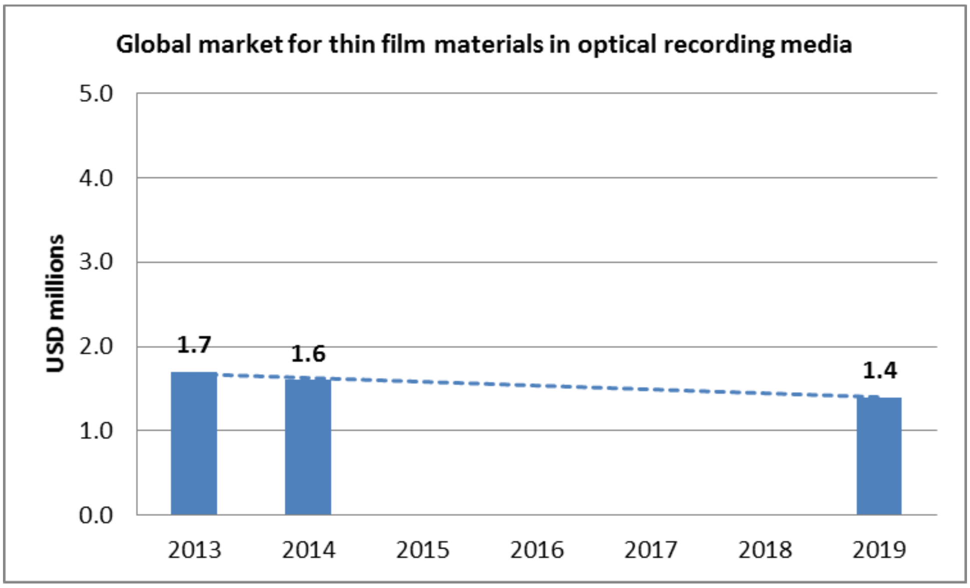
E Optical recording media

The most common types of optical recording media (i.e. audio CD and video DVD) generally have a 50-nm thick reflective aluminium film layer that is sputtered onto a polycarbonate substrate and spin-coated with a protective lacquer coating. The newer blu-ray disc (BD) contains a similar reflective layer[281].

Market data and forecasts

In 2013, global consumption of nanostructured aluminium film materials in the production of optical recording media (e.g. CD and DVDs) was about 52 metric tons, with a value of USD 1.7 million. In the near to mid-term, consumption of nanostructured aluminium film materials for CDs and DVDs will be driven by projected trends in unit disc sales. Data on total global shipments of optical recording media (e.g. CDs, DVDs and Blu-Ray discs) are hard to obtain, but indications are that they are declining as alternative content delivery and storage technologies gain market share. The figures in the table below assume that shipments of optical storage media are decreasing at a CAGR of -3.8%, with a proportional reduction in consumption of nanostructured aluminium thin film materials.

[281] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.63



Source: BCC Research

Figure 8-10: Global market for thin film materials in optical recording media

F Optical fibre cladding

Over-cladding is the process of placing a fibre into a capillary tube and collapsing the capillary tube until it fuses with the fibre[282]. Nanoscale silica particles are used to produce the over-cladding or outer layer of optical fibres that confine the information-carrying light pulses to the core of the fibre. The over-cladding tube is generally formed separately from the inner cladding and core, and the components are then brought together in the preform that is drawn to form the finished optical fibre. The over-cladding does not have to meet the demanding purity and uniformity specifications of the core and inner cladding, and, as a result, efforts to improve manufacturing efficiency and lower the cost of optical fibre manufacturing processes have focused on the over-cladding[283].

Company snapshot: Belden Electronics GmbH

Belden has been a leader in the design and manufacture of insulated wire, cable and related products for over 100 years. Today it is a world-class supplier of signal transmission solutions and it offers over 3,000 cable and connectivity components (including fibre optics) for applications in computer/networks, CATV (community antenna TV), industrial, entertainment and security. As with other producers of optical fibres, Belden uses silicon nano particles for fibre cladding to improve optical properties.

The Company was founded by Joseph C. Belden in 1902 in Chicago, US. In 2004, Belden merged with Cable Design Technologies Corp. and has since transformed itself from a cable company to a signal transmission solutions provider with a product portfolio including cable, connectivity and networking products. In 2014, Belden revenues were USD 2.3 billion.

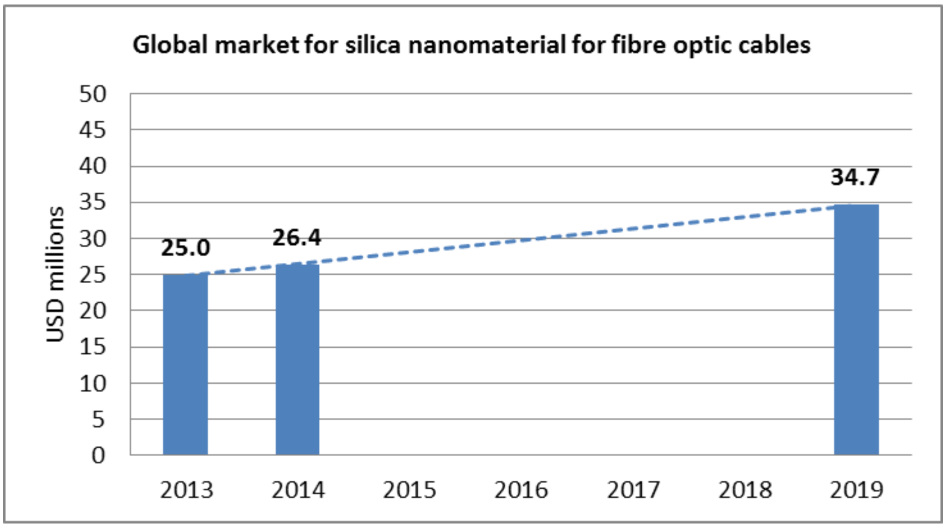
In their portfolio are products such as multi-conductor, paired, coaxial, flat and fibre optic cables, portable cordage, moulded cable assemblies, hook-up wire and lead wire. Key market brands include: Brilliance® entertainment/broadcast cables, New Generation® sound, security and alarm cables, IndustrialTuff® industrial/factory floor cables, residential cables, and DataTwist® networking cables.

Market data and forecasts

Global consumption of silica thin film nanomaterials used for fibre optic cladding was estimated at 1,640 metric tons, worth USD 25 million, in 2013. Over the near to mid-term, the market for silica-

[282] AFL Specialty Fiber Optic Components and Services, product info
[283] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.64

based nanoscale coatings will be driven chiefly by trends in output of fibre optic cable. The output of fibre optic cable is projected to grow from 164 million kilometres (km) in 2013 to 173.2 million km in 2014 and 227.6 million km in 2019, a CAGR of 5.6% over the next five years. The projections in the following table assume that consumption of silica-based nano thin film materials grows in proportion to the output of optical fibre cable.



Source: BCC Research

Figure 8-11: Global market for silica nano material for fibre optic cables

G ANTI-SCRATCH/ ANTI-STICK COATINGS

In recent years, as the optical–electronic industry has developed, polymeric materials have been gradually increasing in importance. Polycarbonate (PC) is a good candidate for eyewear applications due to its low weight and transparency. In the case of polycarbonate lenses, the deposition of anti-scratch (AS) coatings on the polymer surface is essential for the improvement of the mechanical behaviour of the lens[284].

There are reportedly several manufacturers of eye-ware and optical equipment that use nanoparticle based anti-scratch coatings. Nanogate AG (Göttelborn, Germany) has developed nanoparticle-reinforced polymeric thin film anti-scratch coatings for Schweizer Optik for eyeglasses and magnifying glasses[285]. UVEX Arbeitsschutz GmbH (Fürth, Germany) sells safety eye-ware that is protected using its nanotechnology-based uvex supravision sapphire coating system[286]. ZEISS (Jena, Germany) has developed its ZEISS PureCoat® PLUS that comprises an anti-scratch hard coating reinforced by nano-particles[287].

Company snapshot: Nanogate AG[288]

The company is based in Göttelborn, Germany, and has been listed in the Entry Standard segment of the Deutsche Börse since 2006. It provides technologically and visually high-quality systems, equipping plastic, metal and other surfaces with new functions and properties. (e.g. scratchproof, chemical resistance, UV protection, easy cleaning, hygienic features, de-misting, anti-static or certain tribological properties). It employs over 550 workers and had sales of EUR 68.6 million in 2014. Nanogate is established in various German cities and in Geldrop, the Netherlands.

As a systems provider, it offers services throughout the value chain, from the purchase of

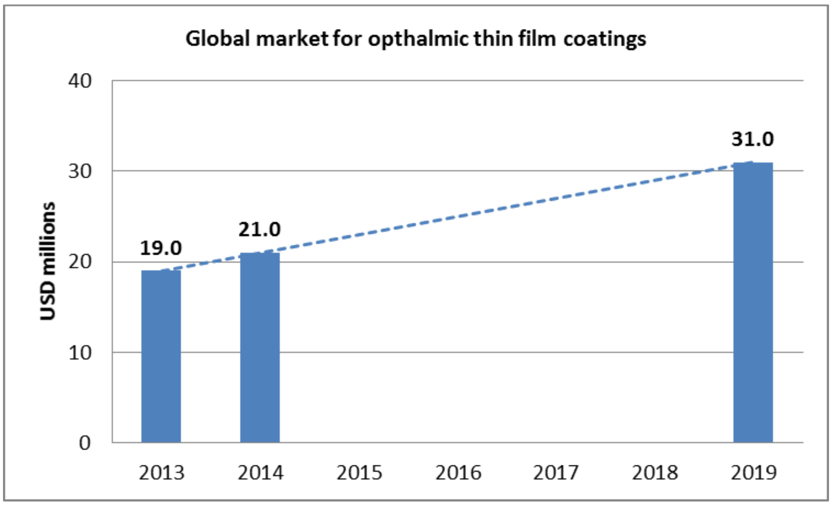
[284] Charitidis C, et al (2004), Optical and nanomechanical study of anti-scratch layers on polycarbonate lenses, Superlattices and Microstructures 36 (2004): 171
[285] Handelsblatt: Nanotechnologie ist die „Next Economy", 12.12.2002
[286] http://www.uvex-safety.com/en/products/safety-glasses/coating-technology-eyewear/
[287] http://www.zeiss.com/vision-care/en_us/products-services/coating-coloured-lenses/coatings/purecoat.html#details
[288] http://www.nanogate.de/en/home

raw materials, to the synthesis and formulation of the material systems, right through to the enhancement and production of the finished surfaces. Nanogate focuses primarily on optically high-quality plastic and metal coatings for all surface types (two and three-dimensional components). In addition, Nanogate develops a broad spectrum of high-performance care products for sport and leisure applications in the consumer goods sector, as well as systems to equip industrial filters with additional properties (e.g. antistatic, flame-retardant, easy-to-clean, scratchproof).

Nanogate AG had 81 patents as of the end of 2014.

Market data and forecasts

Ophthalmic coatings form a relatively mature market segment that is expected to grow at a CAGR of 8.1%, from 2014 through 2019. Global sales accounted in 2013 for USD 19 million and are expected to reach USD 31 million in 2019[289].



Source: BCC Research

Figure 8-12: Global market for ophthalmic thin film coatings

H Organic LEDs – lighting

An OLED 'light bulb' is a thin film of material that emits light. OLED is the only technology that can create "area" lighting panels on a large scale (as opposed to point or line lighting enabled by LEDs and fluorescent bulbs). OLEDs can be used to make flexible and transparent panels, and can also be colour-tunable. OLEDs emit softly diffused light making them the closest light source to natural light (with the exception of the old incandescent lamps)[290]. Some of the activities in this area include:

- Applications in flexible signs and lighting are being developed[291]. Philips Lighting have made OLED lighting samples under the brand name "Lumiblade" available online since 2009[292] and Novaled AG based in Dresden, Germany, introduced a line of OLED desk lamps called "Victory" in September, 2011[293].
- Osram AG (Munich, Germany), the lighting subsidiary of Siemens AG, took a step closer to full commercial production of OLED lighting in 2011 with the opening of a pilot-line manufacturing plant for organic light-emitting diodes (OLEDs). The facility in Regensburg West, which currently employs 220 people, required an investment of EUR 20 million[294]. At about the same time, Philips announced it was expanding its production capacity for Lumiblades as other companies began to enter the market.

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[289] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.157
[290] http://www.oled-info.com/oled-light
[291] Michael Kanellos, "Start-up creates flexible sheets of light", CNet News.com, December 6, 2007
[292] http://oledworks.com/
[293] TMC NEWS: New OLED Luxury Luminaire Series Launched Under German Brand Name Liternity®, September 13, 2011
[294] LEDs magazine: Osram opens OLED pilot-production facility in Germany

- Also in 2011, Verbatim's VELVE line was introduced, based on Mitsubishi Chemical Corporation's materials and production process to manufacture colour (RGB) tunable OLED panels.
- Mitsubishi Chemical Corporation announced in 2014 the development of an organic light-emitting diode (OLED) panel with a life of 30,000 hours, twice as much as conventional OLED panels. The new longer-life OLED module has a range of uses in offices, households and medical facilities. The new product will be manufactured by Pioneer OLED Lighting Devices, a Pioneer subsidiary, and sold by MC Pioneer OLED Lighting, a joint marketing venture of Mitsubishi Chemical and Pioneer[295].
- Konica Minolta recently started mass-producing flexible OLED lighting panels in what is probably the world's most advanced OLED fab - a roll-to-roll flexible OLED lighting fabrication facility that has the capacity to produce a million flexible and colour-tunable OLED panels each month. The Japanese company recently announced that it shipped 15,000 flexible OLEDs to a Japanese tulip festival - by far the largest OLED installation to date[296].

Company snapshot: Philips

Koninklijke Philips N.V. (Royal Philips, commonly known as Philips)[297] is a Dutch technology company headquartered in Amsterdam with primary divisions focused in the areas of electronics, health-care and lighting. It was founded in Eindhoven in 1891 two members of the family. It is one of the largest electronics companies in the world. At the end of 2013, Philips had 111 manufacturing facilities and 59 R&D facilities across 26 countries, plus sales and service operations in around 100 countries.

Philips is organised into three main divisions: Philips Consumer Lifestyle (formerly Philips Consumer Electronics and Philips Domestic Appliances and Personal Care), Philips Healthcare (formerly Philips Medical Systems) and Philips Lighting. Philips achieved total sales of EUR 22.4 billion in 2014 (EUR 6.87 billion from lighting) and had a brand value of USD 10.3 billion. At the end of 2014, Philips had almost 114,000 employees, almost 38,000 in lighting (one third of all employees), 33% in Philips Healthcare and 15% in Philips Consumer Lifestyle, the remainder being employed across the group. Philips invested a total of EUR 1.64 billion in research and development in 2014, equivalent to 7.6% of sales. The company holds around 54,000 patent rights, 39,000 trademarks, 70,000 design rights and 4,400 domain name registrations. It filed 1,680 patents in 2014.

MARKET DATA AND FORECASTS[298]

The market for OLED lighting was negligible in 2013 and 2014. Most of this early market was in niche applications such as high-end residential lamps and commercial showroom installations. In the longer term, though, potential markets for OLED lighting include architectural lighting and backlighting for displays and signage, switches, keypads, instrument panels and possibly automotive dashboards. It is estimated that the total market for OLED lighting could reach USD 765 million by 2019.

Backlighting applications are likely to represent the main market growth for OLED lighting between 2014 and 2019, with an initial emphasis on backlighting for cell-phone and PDA displays, later expanding into medium and large flat-panel displays. The main competitor for OLED backlights comes from LEDs, which started replacing cold cathode fluorescent lighting (CCFL) backlighting in around 2004. It is estimated that the global market for LED backlighting was worth USD 3.2 billion in 2013 and could reach USD 8 billion by 2019. It is difficult to forecast the potential market for OLED backlighting, which has not yet reached the market in significant quantities. However, based on the market history of LED backlights, it is estimated that the market for OLED backlights could reach USD 1 billion by 2019, with the OLED thin film materials accounting for about 50% of the total cost of the backlighting, or USD 500 million.

[295] Xinhua News Agency: Japanese company doubles diode panel's life span, Oct. 13, 2014
[296] http://www.oled-info.com/oled-light
[297] *http://www.2014.annualreport.philips.com/*
[298] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.161

Table 8-4: Global market for OLEDs by type

	2019
Type of Lighting	USD million
Backlighting	500
Architectural Lighting	265
Total	765

Source: BCC Research

OLED lights generally cast a diffuse light, which makes them more of a competitor for fluorescent tube lights than for directional lights such as incandescent lights or LEDs. The global fluorescent lighting market is expected to reach at least USD 26.5 billion by 2019.

Given the current focus on energy-efficient lighting, OLEDs may capture 2% of the market to that held by compact fluorescent lights (CFLs) and other fluorescent lighting, resulting in sales of around USD 500 million by 2019. If the OLED thin film materials represent 50% of the total cost of the lamps, the value of the materials market for OLED thin films would be USD 265 million in 2019.

I High-pressure discharge lamp tubes

Nanostructured ceramic materials fabricated from alumina nano-powders have found commercial applications in the translucent alumina arc tubes of high-pressure discharge (xenon) lamps. In these applications, nanoparticles are normally used in conjunction with larger, submicron- or micron-scale powders to obtain the desired properties in the final sintered part. Each arc tube consumes about 3g to 5g of alumina powder, approximately 30% of which has nanoscale dimensions[299].

Company snapshot: OSRAM

OSRAM Licht AG is a multi-national lighting manufacturer headquartered in Munich, Germany. It was founded in 1919 by the merger of the lighting businesses of Auergesellschaft, Siemens & Halske and Allgemeine Elektrizitäts-Gesellschaft (AEG). The name comes from the elements needed to produce light filaments at the time – OSmium and tungsten (or wolfRAM).

From 1978 to 2013, Siemens was the sole shareholder in OSRAM. On 5 July 2013, OSRAM was spun off from Siemens and the Group has been listed on the stock exchange as OSRAM Licht AG. It employs around 34,000 people throughout the world and has operations in over 120 countries. The company generated a revenue of more than EUR 5.1 billion in 2014. OSRAM business activities have been focusing on light for over 100 years. The company's North American operation is Osram Sylvania, headquartered in Wilmington, Massachusetts; products sold in Canada, Mexico, United States and United States territories are sold under the Osram Sylvania brand name.

Being one of the two leading light manufacturers in the world, the company's portfolio covers the entire value chain from components – including lamps, electronic control gear and optical semiconductors such as light-emitting diodes (LED) – as well as light management systems and lighting solutions. With LED-based products making up a share of 36% of the total turnover, the company is setting significant trends with regard to technological changes in the lighting market. More than 60% of research & development expenditures are in the SSL area (solid state lighting).

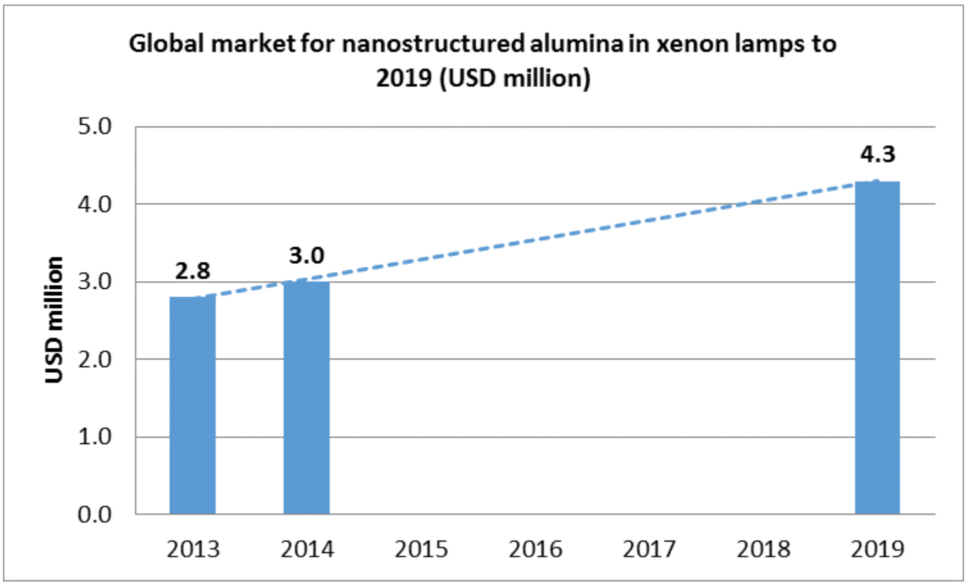
See also: http://www.osram.com/

Market data and forecasts

Total consumption of nanostructured ceramic alumina materials in high-pressure discharge (xenon) lamp tubes in 2013 was 11 metric tons with a value of USD 2.8 million. Trends in the number of automotive vehicles sold equipped with these lamps are expected to be the main market driver. Once found only in luxury cars, xenon headlamps are available in a growing number of vehicles. It is estimated that the automotive market for xenon lamps will at a CAGR of 7.5% from 2014 to 2019 and that the market for nanostructured ceramic alumina will grow at the same rate, reaching a

[299] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.75

market value of USD 4.3 million in 2019.



Source: BCC Research, 2014

Figure 8-13: Global market for alumina in xenon lamps

J NEAR-FIELD OPTICAL MICROSCOPES

Scanning near-field optical microscopy (SNOM), also known as near-field scanning optical microscopy (NSOM), is a scanning probe technique developed to surpass the spatial resolution constraints that traditionally limit conventional optical microscopy[300]. SNOM is suitable for studies on the mesoscopic scale (several tens to hundreds of molecular dimensions). It has become an important tool in research and applications of semiconductors, organic layers and membranes, biological materials and optics. The technique exists under two different names: the name scanning near-field optical microscopy (SNOM), used by the IBM group, stresses its focus on the scanning part of the instrument because of IBM's previous invention of the scanning tunnelling microscope (STM)[301] while NSOM results from the focus of the Cornell group on near-field optics.

Near-field scanning optical microscopy is continuing to grow in use, for applications requiring very high optical resolution. SNOM can be used as an imaging/microscopy instrument and for specimen manipulation, fabrication, and processing on a nanometric scale. The increasing number of non-imaging SNOM applications include precision laser-machining, nanometre-scale optical lithography, and light-activated release of caged biochemical compounds[302] [303].

SNOM is currently still in its infancy, and more research is needed on developing improved probe fabrication techniques and more sensitive feedback mechanisms. The future of the technique may rest in refinement of aperture-less near-field methods (including interferometry), some of which have already achieved resolutions on the order of 1 nanometre. However, typical resolutions for most SNOM instruments range around 50 nanometres, which is only 5 or 6 times better than that achieved by scanning confocal microscopy and is costly in terms of time and complexity in achieving good results. One significant advantage of SNOM that remains is its ability to provide optical and spectroscopic data at high spatial resolution and with simultaneous topographic information[304].

[300] Huckabay H. A. et al. (2013), Near-Field Scanning Optical Microscopy for High-Resolution Membrane Studies, Methods Mol Biol. 2013; 950: 3734.
[301] Kovar M et al. (2015), NSOM: Discovering New Worlds, in: Photonics Handbook®
[302] http://www.olympusmicro.com/primer/techniques/nearfield/nearfieldintro.html
[303] "Caged" compounds are biologically active molecules that have a photolabile protecting group attached to a significant functional group to render the molecule biologically inert. Their use is derived from the use of light to remove the protecting group and release the biologically active molecule. See http://conway.chem.ox.ac.uk/Caged_compounds.html
[304] http://www.olympusmicro.com/primer/techniques/nearfield/nearfieldintro.html

Company snapshot: NT-MDT

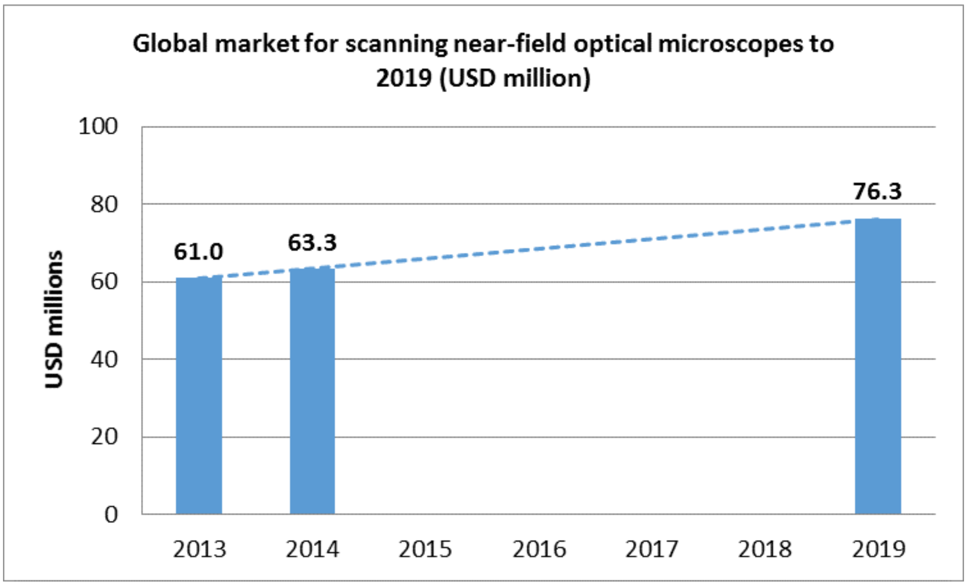
NT-MDT Co. develops equipment for nanotechnology research. The company was founded in 1989 and is based in Moscow (Russian Federation) with more than 20 representative offices and distribution centres in Ireland, the Netherlands, China, and the United States. In the past five years, the number of installed instruments of NT-MDT has grown to over 4000. It is known as a trendsetter in atomic force microscopy (AFM) with state-of-the-art design and a large range of devices. Its microscopes have won many awards including (four times) the prestigious R&D 100 Award.

The NT-MDT portfolio includes the scanning probe microscopes (SPM) for higher education needs; fully automated AFM/STM (scanning tunnelling microscope) instruments for scientific and industrial research centres; probe 'nano-laboratories' integrating the whole spectrum of modern techniques with AFM; modular 'nano-factories' combining the range of equipment and techniques necessary for processing and quality assurance of devices and elements of micro- and nano-electronics; accessories, probes, testing samples and calibration gratings for the probe microscopy.

See also: www.ntmdt.com

MARKET DATA AND FORECASTS

The market for near-field optical microscopes was worth USD 61 million in 2013. Sales of SNOMs are expected to grow at a CAGR of 3.8% over the near to mid-term. The growth of the SNOM market is largely driven by a movement away from conventional optical microscopy toward advanced forms of microscopy, partly due to the growing need to image structures on a very small (e.g. nano) scale, as well as the development of instruments and technologies that extend the range of advanced microscopic tools[305].



Source: BCC Research

Figure 8-14: Global market of scanning near-field optical microscopes

K ADVANCED OPTICAL LITHOGRAPHY TOOLS

Optical lithography is the patterning of masks and samples with photoresist prior to other processing steps (e.g. deposition, etching, doping)[306]. The technology has enabled the size-reduction of

[305] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.189
[306] http://lnf-wiki.eecs.umich.edu/wiki/Optical_lithography#Processes

semiconductor devices and integrated circuits[307]. Until recently, chip manufacturers have been able to keep pace with shrinking feature sizes by modifying existing optical lithography technologies through constant refinements in light sources, lens design and photomask technology. Now, as semiconductor manufacturers pass the 28-nm node and begin reaching the 26-nm node on the technology road map, they are moving to adopt advanced optical lithography technologies developed specifically for the creation of nanoscale patterns and structures on semiconductor chips, particularly optical immersion lithography and optical (laser) mask-less lithography[308].

Immersion lithography - the more established of these two technologies - is a technology in which lithographic exposure is applied to a resist-coated wafer via purified water that is introduced between the projection lens of a semiconductor exposure system (scanner) and the wafer[309]. This technique effectively shortens the wavelength of the light involved while retaining resolution, and it has the potential to extend the capabilities of optical lithography much farther than previously thought. Intel reportedly plans to continue using immersion lithography at the 22-nm node and even down to the 11-nm node[310]. The only manufacturers that are currently offering immersion lithography systems are ASML, Canon, and Nikon[311].

Mask-less optical lithography is enabling the development of a competing technology. In mask-less lithography, the radiation used to expose a photosensitive is in the form of a narrow beam[312]and no mask is needed. The beam is used write the image into the photoresist, one or more pixels at a time. The forms of mask-less lithography include: scanning electron-beam lithography (SEBL), focused ion-beam (FIB) lithography, multi-axis electron-beam lithography (MAEBL), interference lithography (IL), mask-less optical-projection lithography (MOPL), zone-plate-array lithography (ZPAL), scanning-probe lithography (SPL), and dip-pen lithography (DPL)[313]. At present, several companies, such as Heidelberg Instruments of Germany and Mycronic of Sweden, have mask-less optical lithography systems on the market, but their products are generally used to generate non-nanoscale features on photomasks[314].

The FP7 project MAGIC (MAsk-less lithoGraphy for integrated circuits (IC) manufacturing) has supported the development of e-beam based mask-less lithography (ML2) technology in Europe with a focus on two parallel lithography tool developments and aiming to develop the required infrastructure for the usage of these tools in an industrial environment[315].

Mapper Lithography[316] (Delft, Netherlands) has developed a new, patented technology for making chips without a mask and using electron beams. This approach enables improved performance and reduces costs. The company´s major innovation is the use of one system through which more than 10,000 parallel electron beams can pass. MAPPER uses fibre-optics, which is capable of transporting a large quantity of information.

Market data and forecasts

It is estimated that optical immersion tool manufacturers delivered about 90 immersion lithography tools in 2013. At a cost of about USD 45 million each, these tools represented a USD 4.1 billion market in 2013. It is expected that the delivery of new optical immersion tools will peak at 127 units (USD 5.7 billion) in 2017, then level off or even decline slightly by 2019, as next-generation nanolithographic technologies such as nanoimprint and extreme ultraviolet lithography begin to come online[317].

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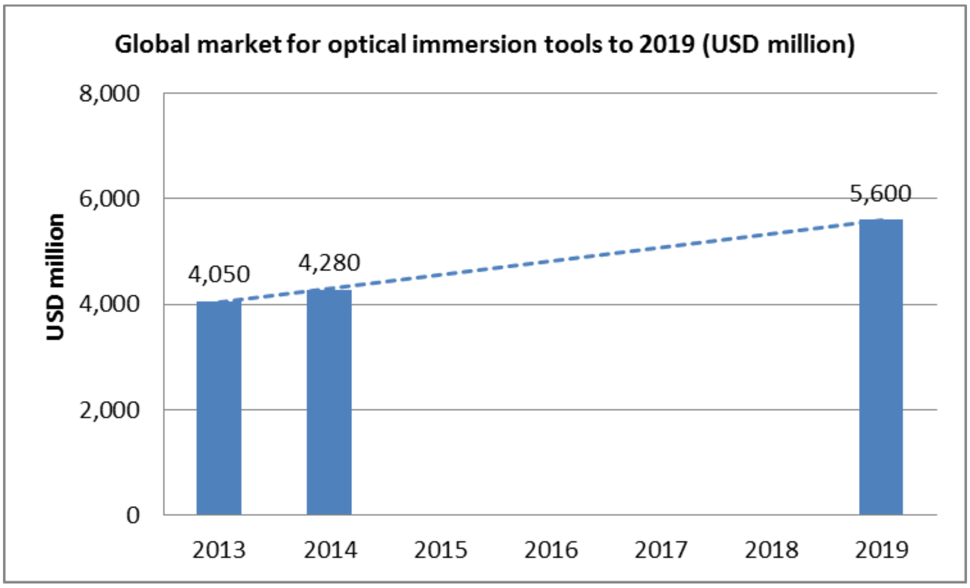
[307] Rothschild M et al. (2003), Recent Trends in Optical Lithography, LINCOLN LABORATORY JOURNAL VOLUME 14, NUMBER 2, 2003: 221
[308] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.98
[309] http://www.nikon.com/about/technology/rd/core/optics/immersion_e/index.htm
[310] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p. 98
[311] EE Times: ASML, Canon, Nikon tip immersion tools, October 7 2006
[312] http://www.definitions.net/definition/MASKLESS%20LITHOGRAPHY
[313] Menon R et al. (2005), Maskless lithography, Materials Today Volume 8, Issue 2, February 2005, p. 26.
[314] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.98
[315] MAGIC Project info Sheet, FP7 ICT – Nanoelectronics
[316] http://www.mapperlithography.com/
[317] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.190



Source: BCC Research, 2014

Figure 8-15: Global market for optical immersion tools

Case study: Rudolph Technologies

Rudolph Technologies, Inc. (New Jersey, US) was established in 1940. Its field is process control metrology systems used in semiconductor device manufacturing. The company specialises in design, development and manufacturing of semiconductor devices. Other services include defect inspection, advanced packaging lithography, thin film metrology, data analysis and software (for microelectronics device manufacturers).

In order to expand its portfolio of products and maintain its stronghold on the advanced packaging market, the company acquired NanoPhotonics GmbH (Germany) in June 2012. This acquisition has been valued at around USD 7.8 million (EUR 5.86 million). The deal enabled Rudolph to include NanoPhotonics' inspection technology and associated intellectual property in its portfolio. The activity revolves around adding tools for inspection of unpatterned wafers and mask blanks. The acquisition also benefitted the portfolio of Rudolph Technologies by bringing it Reflex TT™, a table-top, manually-loaded wafer inspection tool for detecting particles, scratches, area defects and micro-roughness on unpatterned wafers and mask blanks.

Through the deal Rudolph acquired all-surface inspection systems (wafer edge, backside and front side) for 200, 300 and 450 mm wafers, along with mask blank inspection systems [3]. This enabled the company to readily penetrate the customer base for unpatterned wafer inspection. This customer base generally comprises of semiconductor manufacturers who require these tools for quality assurance and yield improvement purposes, silicon wafer manufacturers and substrate suppliers for compound semiconductors].

It may be expected that the highly evolving and rapidly growing advanced packaging market will soon require expertise in all-surface inspection, which in turn, will be met by adding the NanoPhotonics operations into existing inspection offerings. The expertise in back-end manufacturing environment has been combined with NanoPhotonics' sub-micron resolution capability in order to deliver high precision solution for customers.

The acquisition was carried out in the second quarter of 2012, which, at that time, was expected to result in a revenue increment of USD 2 million per quarter, so USD 8 Million per annum (EUR 6.2 Million). Revenue in 2012 was USD 218 million (EUR 163.9 million), implying that the NanoPhotonics component was approximately 3.8% of overall revenues on an annualised basis.

At the end of the Financial Year 2014-2015, the revenue was USD 181.2 million (EUR 136.2 million). In the same period, the R&D spending accounted for almost USD 40 million (EUR 30.1 million) and it is estimated that around 30% i.e. USD 12 million (EUR 9 million) was *dedicated to nanotechnologies.*

One of the newest additions to the product line of Rudolph Technologies is the macro defect inspection tool, the NSX®330 Series. The NSX 330 Series enables swift macro-defect inspection and 2D and 3D metrology for advanced packaging applications directed towards various components of the mobility and the growing Internet of Things (IoT) markets.

The introduction of the new line of products can be looked upon as the next generation of the previous product line i.e. the NSX 320. According to the company sources, the NSX 330 Series brings a 30% 2D inspection throughput improvement as compared to the NSX 320 System. This new line of products is dedicated to meet the inspection and metrology requirements for advanced packaging applications from foundries, integrated device manufacturers (IDMs) and outsourced assembly and test (OSAT) manufacturers. The product line facilitates 3D capability, precise ability to simultaneously measure topography and thickness with nanometre-level repeatability.

Rudolph Technology has been active in licensing technologies from various institutes and corporates e.g. Rudolph's PULSE technology for opaque film metrology, originally licensed from Brown University. The technology uses an ultrafast flash of laser light to generate a sound wave which penetrates an opaque film stack. When the sound wave encounters a film interface, an echo returns to the surface. The time between sound induction and echo detection provides a direct measurement of film thickness.

The customer base consists of manufacturers of logic, memory, data storage, flat panel and application-specific integrated circuit devices. Rudolph Technologies has closed a number of deals in 2015 and moved further in acquiring technologies from other companies. For example, during Q3 2015, Rudolph acquired the inspection technology of Stella Alliance, LLC, a patented illumination, auto-focus and image acquisition technology for the identification of defects that are not visible with current techniques. Also, in June 2015, the company closed a deal with Robert Bosch GmbH to supply configurations of its F30 inspection system for steps in the front- and back-end fabrication processes of MEMS (microelectromechanical systems) devices. The systems will help Bosch handle a wide range of substrates used in complex MEMS processes and provides handling solutions for frameless, ultrathin, film-frame and thicker non-traditional substrates. It is further expected that Rudolph Technologies will utilise the expertise sourced from NanoPhotonics GmbH in all-surface inspection systems.

See also: http://www.rudolphtech.com/

8.3.3 Emerging application markets

This section looks at the emerging applications of:

- Flat-panel displays;
- Digital image sensors;
- Transparent conducting electrodes;
- Super lenses;
- Photonic add/drop filters;
- Optical switches;
- Optical amplifiers (op amps);
- Next generation nano-lithographic tools; and
- Holographic memory.

A Flat panel displays

Quantum dots (QDs) are nanoscale semiconductor materials with unique optical properties as the light frequency (and hence colour) depends on the size of the QD. The optoelectronic properties of QDs, such as their band gap, can be tuned as a function of particle size and shape. Thus, their photoluminescence can be tuned to specific wavelengths by controlling their particle dimensions.

Organic materials are promising for use in light-emitting devices, including displays, because they can be made inexpensively, can be deposited on flexible substrates, and can be made to shine brightly[318].

QD Vision Inc. combines QD materials with the organic molecules and processing techniques of plastic electronics to create a new class of solid-state displays. Quantum dots in a colloid have been incorporated into the display technology under development at the company. QD Vision Inc. and Sony Corporation began to sell LCD TVs applied with Color IQ™ in the first half of 2013.

QDEF™, jointly developed by Nanosys and 3M, has been in use in the 7-inch and 8.9-inch Kindle Fire HDX tablets of Amazon since November 2013[319].

QD Vision is also working on flat panel displays based on QD-LED technology that could reach the market by 2019. The structure of QD-LED is similar to organic light-emitting diode (OLED) but is different in terms of the light source. The light source of a QD-LED comes from cadmium selenide (CdSe) nanocrystals, or quantum dots. If QD-LED becomes successfully developed, its display quality will be much better than its predecessor especially on pure colour quality[320].

It is likely that quantum dot displays, by analogy with OLEDs, will remain a niche product through 2019[321].

B Digital image sensors[322]

Digital image sensors can be used to record electronic images. The most commonly recognised application of the digital image sensor is the digital camera. In digital cameras, the image sensor is used in conjunction with a colour separation device and signal processing circuitry to record images. The two main technologies used to fabricate the sensors are CCDs (Charge Coupled Devices) and CMOS (Complementary Metal-Oxide Semiconductors)[323].

InVisage Technologies (Menlo Park, Calif.) is commercialising QuantumFilm (QF) technology to replace the conventional complementary metal-oxide semiconductor (CMOS) image sensor. QF technology works by suspending quantum dots within a special polymer film. The film is then “spun” or painted on top of a traditional CMOS wafer. The quantum dot film captures all the light that hits the top of the chip and sends it directly to the silicon chip. In a conventional CMOS image sensor, light typically has to pass through layers with metal connections before it hits a photo detector, which blocks out about half the photons. By putting the film on top of the chip, and by having more efficient materials, InVisage proposes to create a sensor that is four times more sensitive to light with twice the dynamic range of the typical CMOS sensor. According to InVisage, its new technology will enable higher resolution for cameras and much better low-light performance, particularly in contrast to the sensors used in today’s camera phones.

InVisage Technologies’ first QuantumFilm image sensors, targeting high-end mobile handsets and smartphones, are scheduled to be deliverd sometime after 2014. It is estimated that 100 million QuantumFilm sensor-equipped handsets will be sold in 2019. QuantumFilm sensors are expected to cost the same as the CMOS sensors they replace (c. USD 5 each) making a total market value of USD 500 million in 2019. The exact cost of the quantum dot film in a QuantumFilm sensor is not known but, according to InVisage, the incremental cost is minimal. For analytical purposes, if the quantum dot film adds 5% to the cost of the sensor, about USD 25 million worth of quantum dots will be required to fabricate the USD 500 million worth of QuantumFilm sensors it is estimated that the market will require in 2019.

C Transparent conducting electrodes

Transparent conducting oxides (TCOs), or transparent electrodes, are electrically conductive materials with a comparatively low absorption of light. They are usually prepared using thin-film technologies and are used in opto-electrical devices such as solar cells, displays, opto-electrical interfaces and circuitries. Glass fibres are nearly lossless conductors of light, but electrical insulators; silicon and compound semiconductors are wavelength-dependent optical resistors (generating mobile

[318] Coe-Sullivan S (2006), The Application of Quantum Dots in Display Technology, Material Matters Volume 2 Issue 1
[319] IHS Technology – Abstract: - Quantum Dot Display Technology - 2014
[320] Headlines an Global News: New Research Improves QD-LED Displays by Using Engineered Quantum Dots, Oct 26, 2013
[321] BCC Research (2014), Nanotechnology: A Realistic Market Assessment p.137
[322] BCC Research (2014), Nanotechnology: A Realistic Market Assessment p.42-43, p.138
[323] https://illumin.usc.edu/101/the-digital-image-sensor/

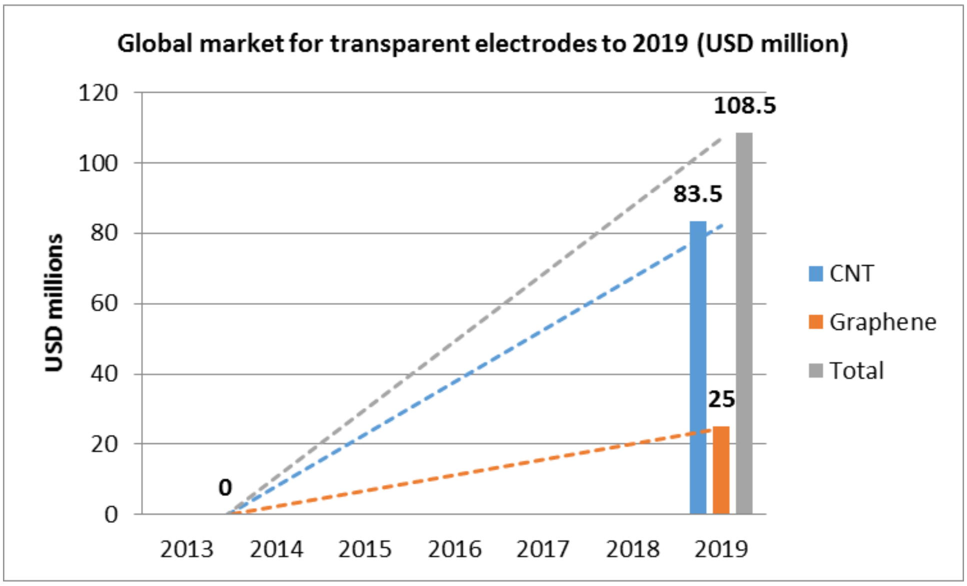
electrons), and dopant-dependent electrical conductors[324]. To date, the industry standard in TCOs is ITO, or tin-doped indium-oxide.

Unidym (Sunnyvale, Calif.) has developed a carbon nanotube-based transparent electrode intended to replace the indium tin oxide (ITO) currently used in such products as touch screens, LCD displays, solar cells and OLEDs. Unidym's CNT-based films are reportedly more mechanically- and chemically-robust than ITO and can be deposited using a variety of low-cost methods. Unidym has been providing samples to potential customers in the touch screen, LCD display, OLED and solar industries. While no date has been set for commercial production of CNT-based films, it is forecast that commercialisation is likely to take place in the 2014 through 2019 time frame[325].

Graphene is another promising material to replace ITO as a TCO in transparent electrodes. The project GLADIATOR, which is funded by the European Commission, has reached its mid-term point and has already achieved some successes. The aim of the project is the cost-effective production of high quality graphene over large surface areas, which can then be used for numerous electrode applications. The usability of such applications will be demonstrated by Fraunhofer FEP by integrating this graphene in OLEDs. With graphene as an electrode, the researchers at the Fraunhofer FEP hope to create flexible devices with higher stability. The GLADIATOR project will run until April 2017. By this time, several types of OLEDs will have been made using graphene electrodes: a white OLED with an area of about 42 cm^2 to demonstrate the high conductivity, and a fully-flexible, transparent OLED with an area of 3 cm^2 to confirm the mechanical reliability[326].

In March 2013, the Chinese firm Chongqing Morsh Technology Co. Ltd received an order from Guangdong Zhengyang Technology Incorporated Company to supply at least 10 million graphene conducting film products per year for five years[327].

Two nanomaterial-based thin film technologies are candidates to replace the indium tin oxide (ITO) currently used in touch screens, LCD displays, solar cells, OLEDs and other electronic devices. Annual consumption of ITO for these applications is approximately USD 1 billion for the material alone (i.e. excluding deposition costs). These new technologies are transparent carbon nanotube-based electrodes (such as the product Unidym is planning to launch in the near future) and graphene-based electrodes. Combined sales of these two transparent electrode materials could approach USD 109 million by 2019, as shown in the figure below[328].



Source: BCC Research, 2014

Figure 8-16: Global market for transparent electrodes to 2019

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[324] Andreas Stadler (2012), Transparent Conducting Oxides — An Up-To-Date Overview. Materials 2012, 5: 661
[325] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.69
[326] http://cordis.europa.eu/news/rcn/128114_en.html
[327] Investorintel: Chinese Firms to launch First Mass Produced 15" Single-layer Graphene Film, March 27, 2013
[328] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.163

D Super-lenses

A practical super-lens (or superlens) is a lens which uses metamaterials to go beyond the diffraction limit. The diffraction limit is a feature of conventional lenses and microscopes that limits their resolution. Many lens designs have been proposed that go beyond the diffraction limit in some way, but there are constraints and obstacles involved in realising each of them[329].

In 2005, researchers at the University of California, Berkeley developed an experimental super-lens using a thin film of silver as the lens and ultraviolet (UV) light. The researchers recorded the images of an array of nanowires and the word "NANO" onto an organic polymer at a resolution of about 60 nanometres. In comparison, current optical microscopes can only make out details down to one-tenth the diametre of a red blood cell, or about 400 nanometres[330]. The researchers had originally foreseen that their super-lens technology could be commercialised by 2010. While this projection has turned out to be overly optimistic, the first commercial applications could be on the market by 2019[331].

In 2010, a research team from Northeastern University fabricated and tested a nano-wire array prototype, described as a three-dimensional (3D) metamaterial-nanolens, consisting of bulk nanowires deposited in a dielectric substrate[332]. The metamaterial nanolens was constructed of millions of nanowires of 20 nanometres in diameter. The lens is able to depict a clear, high-resolution image of nano-sized objects because it uses both normal propagating EM radiation, and evanescent waves to construct the image. Super-resolution imaging was demonstrated over a distance of 6 times the wavelength (λ), in the far-field, with a resolution of at least λ/4. This is a significant improvement over previous research and demonstration of other near field and far field imaging[333].

E Photonic add/drop filters

An important device for optical communications and in many other applications is a channel-drop filter. Given a collection of signals propagating down a waveguide (called the bus waveguide), a channel-drop filter picks out one small wavelength range (channel) and reroutes (drops) it into another waveguide (called the drop waveguide)[334].

A number of technologies are used in channel add/drop filters, including Mach–Zehnder interferometers, grating-assisted mismatched couplers and multiport circulators. However, existing add/drop filters can only extract and redirect a few distinct, well-separated wavelengths. Accordingly, known drop filters are not fully satisfactory for use as an extraction device in a wavelength division multiplexing (WDM) system that requires the capability of extracting carrier signals carried by light having a large number of different wavelengths. The use of nanocomposites should make it possible to construct a channel add/drop filter that reroutes the desired channel into the drop waveguide with 100% transfer efficiency (i.e. no losses, reflection or cross-talk), while leaving all other channels in the bus waveguide to propagate unperturbed. While there are no nanocomposite add/drop filters are currently on the market, they are seen as one of the most promising applications of these materials in photonics applications[335].

The market for photonic crystal add/drop filters is projected to grow from zero in 2013 and 2014 to USD 43.3 million in 2019 (with sales of all types of optical add/drop filters approaching USD 1.4 billion by 2019). If companies developing photonic crystal add/drop filters can bring a commercial project to market in the next few years, it is forecast that they could capture 10% of the total market by 2019, for total sales of USD 140 million. For the optical industry as a whole, material costs represent nearly one-third of the total value of deliveries, implying that consumption of PBG nanocomposites used to manufacture add/drop filters might be approximately USD 43 million in 2019[336].

[329] Pendry, J. B. (2000). "Negative Refraction Makes a Perfect Lens" Physical Review Letters 85 (18): 3966–9.
[330] UC Berkely news: New superlens opens door to nanoscale optical imaging and high-density optoelectronic devices, 21 April 2005
[331] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.71
[332] Prototype super-resolution metamaterial nanonlens. Nanotechwire.com. 2010-01-18
[333] Casse, B. D. F.; Lu, W. T.; Huang, Y. J.; Gultepe, E.; Menon, L.; Sridhar, S. (2010). "Super-resolution imaging using a three-dimensional metamaterials nanolens". Applied Physics Letters 96 (2): 023114.
[334] http://ab-initio.mit.edu/photons/ch-drop.html
[335] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.91
[336] BCC Research (2014), Nanotechnology: A Realistic Market Assessment p.184

F OPTICAL SWITCHES

Optical switches are all-optical fibre-optic switching devices that maintain the signal as light from input to output. In this they differ from traditional switches that connect optical fibre lines which are electro-optic. Electro-optic switches convert photons from the input side to electrons internally in order to do the switching and then convert back to photons on the output side. Although some vendors call electro-optical switches "optical switches," true optical switches support all transmission speeds. Unlike electronic switches, which are tied to specific data rates and protocols, optical switches direct the incoming bit stream to the output port no matter what the line speed or protocol (IP, ATM, SONET). Optical switches may also separate signals at different wavelengths and direct them to different ports[337]. Quantum dots can further help to improve the performance of all-optical switches by allowing for higher switching speeds, smaller size and lower power consumption.

In 2003, Evident Technologies, Inc. issued a United States Patent (Number 6,571,028) for an all-optical switch or optical transistor. The optical transistor is based upon a saturable absorber or switch using the company's EviDots semiconductor nanocrystal quantum dot technologies. The optical switch has the potential to switch at speeds up to thousands of times faster than current generation optical switching[338]. The quantum dots, which are manufactured of lead sulphide or lead selenide via a thermal precipitation or colloidal growth process, are contained in a matrix or glass, silicon or other material. The intensity of light required to saturate the absorber depends on the size and composition of the quantum dots, and the concentration of dots determines how thick a slab of matrix material is required to produce a given change in intensity of the signal[339].

No quantum dot optical switches are currently on the market, and the timing of their eventual commercial introduction is unknown. However, given their advantages versus competing technologies, it is forecast that quantum dot switches could reach the market before 2019 and the overall optical switch market could exceed USD 1.2 billion by 2019. It is difficult to quantify quantum dot switches' potential share of the 2019 optical switch market with any certainty, especially in view of uncertainty about the timing of their introduction. However, if they capture 2% to 5% of the optical switch market, the market value would be USD 24 million to USD 60 million (or a mean of USD 42 million) by 2019. If material costs represent nearly one-third of the total cost of these devices, the market for PBG nanocomposites in optical switches could reach USD 14 million by 2019[340].

G OPTICAL AMPLIFIERS (OP AMPS)

In order to transmit signals in optical communication systems over long distances (>100 km) it is necessary to compensate for attenuation losses within the fibre. Initially this was accomplished with an optoelectronic module consisting of an optical receiver, a regeneration and equalisation system, and an optical transmitter to send the data. Although functional, this arrangement is limited by the optical to electrical and electrical to optical conversions. Optical amplifiers have been developed to overcome these drawbacks. Currently the two types of optical amplifiers in most common use are semiconductor optical amplifiers (SOA) and rare earth doped fibre amplifiers (erbium – EDFA 1500 nm, praseodymium – PDFA 1300 nm)[341].

Optical amplifiers having nano-sized semiconductor particles, called quantum dots, show attractive features such as an ultra-wide operating wavelength range, suppressed waveform distortion in high power output, and capability of noise reduction (signal regeneration) by limiting amplification. With these features, the quantum-dot devices have been developed targeting applications in optical communication systems such as inline, booster, and preamplifiers, and are presently in the stage of commercialisation. The application is not limited to optical amplifiers, but also includes the light sources for sensors, gyroscopes, optical coherence tomography, etc., and the gain elements integrated into wavelength-tuneable lasers and mode-locked lasers[342]. While the development of quantum dot amplifiers has proceeded rapidly, commercialisation appears to be at least several years away. Reportedly there is still much room for improving the quality of the crystal to eliminate polarisation sensitivity and gain inequality. A further commercial obstacle to commercialisation of quantum dot amplifiers is telecommunications carriers' large investment in existing amplifier

[337] http://www.pcmag.com/encyclopedia/term/48554/optical-switch
[338] ScienceBlog: Evident Technologies Granted US Patent for Optical Switch based on Quantum Dots, Jun 9, 2003
[339] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.91
[340] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.184
[341] Kostuk R (2006), Optical Amplifiers, mimeo
[342] Akiyama T, et la. (2006), Quantum-Dot Semiconductor Optical Amplifiers, IEEE LEOS - LASERS & ELECTRO-OPTICS SOCIETY Newsletter, February 2006 Volume 20, Number 1, p.11

technologies, especially erbium amplifiers[343].

Nanoparticle-based optical amplifiers were not yet available commercially in 2013 and 2014. Global sales of all types of optical amplifiers are projected to reach USD 2.8 billion by 2019. If quantum dot PBG nanocomposite devices can capture 10% of this market, the forecast sales would be USD 280 million in 2019. At one-third of the total cost of optical amplifiers for materials, the related consumption of quantum dot PBG nanocomposites is projected to reach USD 93.3 million by 2019[344].

H Next-generation nanolithography tools

Mainstream optical lithography is ultimately limited by diffraction and, for some time, shorter wavelength alternatives have been pursued to prepare for post-optical applications. As a result, there is an urgent need for a next-generation lithography (NGL) technology, namely extreme ultraviolet (EUV), mask-less and nanoimprint lithography[345].

Extreme UV Lithography (EUVL) is generally accepted as the leading candidate for next generation lithography[346]. Extreme ultraviolet lithography (EUVL) further extends optical lithography by using wavelengths in the range of 11 to 14 nm to shrink the size of features printed while maintaining k1 values at acceptable levels[347]. However, there have been repeated delays in the commercialisation of EUVL, which contributed to Intel's decision to continue using immersion lithography beyond the 22-nm node, but Intel has said it plans to use EUVL for production at the 10-nm level by 2017. TSMC has also emphasised EUVL in its future plans[348].

While EUVL is still to overcome several obstacles to commercialisation, there are two other possible alternative technologies to succeed optical lithography: mask-less lithography and nanoimprint lithography.

In mask-less lithography, the radiation that is used to expose a photosensitive emulsion is not projected from, or transmitted through, a photomask. Instead, most commonly, the radiation is focused to a narrow beam[349]. The beam is then used to directly write the image into the photoresist, one or more pixels at a time. The forms of mask-less lithography include: scanning electron-beam lithography (SEBL), focused ion-beam (FIB) lithography, multi-axis electron-beam lithography (MAEBL), interference lithography (IL), mask-less optical-projection lithography (MOPL), zone-plate-array lithography (ZPAL), scanning-probe lithography (SPL), and dip-pen lithography (DPL)[350]. An alternative method, developed by Micronic Laser Systems or Heidelberg Instruments, is to scan a programmable reflective photomask, which is then imaged onto the photoresist. This has the advantage of higher throughput and flexibility. A key advantage of mask-less lithography is the ability to change lithography patterns from one run to the next, without incurring the cost of generating a new photomask. This may also prove useful for double patterning[351].

Nanoimprint lithography (NIL) is another novel method of fabricating micro/nanometre scale patterns with low cost, high throughput and high resolution. Unlike traditional optical lithographic approaches, which create patterns byusing photons or electrons to modify the chemical and physical properties of the resist, NIL relies on direct mechanical deformation of the resist and can therefore achieve resolutions beyond the limitations set by light diffraction or beam scattering that are encountered in conventional lithographic techniques. The resolution of NIL mainly depends on the minimum template feature size that can be fabricated. Compare with optical lithography and next generation lithography (NGL), the difference in principles makes NIL capable of producing sub-10 nm features over a large area with a high throughput and low cost. Compared to other lithography processes and next generation lithography with nanoscale resolution, such as e-beam lithography and extreme ultraviolet lithography (EUVL), the most prominent advantage of NIL is its ability to pattern 3D and large-area structures from micron to nanometre scale and its potential to do so at a high throughput and low cost[352]. Canon recently acquired the semiconductor unit of Molecular Imprints (MII), a

[343] BCC Research (2014), Nanotechnology: A Realistic Market Assessment p.92
[344] BCC Research (2014), Nanotechnology: A Realistic Market Assessment p.185
[345] Semiconductor Engineering: Waiting For Next-Generation Lithography, January 23rd, 2014
[346] Malone C, Smith B (2011), Longer Wavelength EUV Lithography (LW EUVL), mimeo.
[347] SPIE Newsroom: EUV lithography update, 31 June 2002
[348] BCC Research (2014), Nanotechnology: A Realistic Market Assessment, p.99
[349] http://www.definitions.net/definition/MASKLESS%20LITHOGRAPHY
[350] Menon R et al. (2005), Maskless lithography, Materials Today Volume 8, Issue 2, February 2005, p. 26.
[351] http://www.definitions.net/definition/MASKLESS%20LITHOGRAPHY
[352] Lan, H, Ding, Y (2010), Nanoimprint Lithography, in: Wang, M. (ed.), Lithography, pp. 656-657

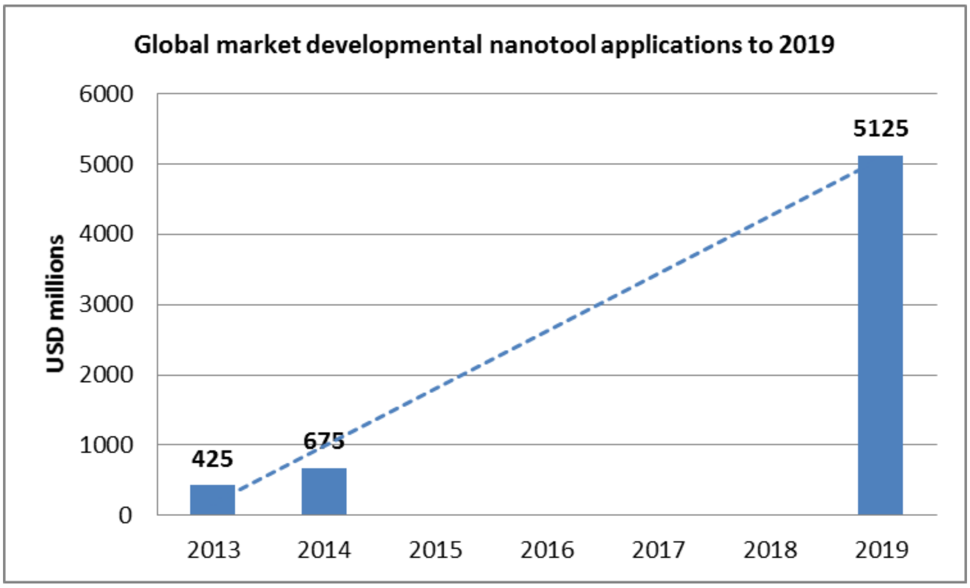
supplier of nanoimprint tools. That group is called Canon Nanotechnologies (CNT)[353].

Table 8-5: Global market for developmental nano-tool applications, through 2019

Applications	2013	2014	2019	CAGR% 2014-2019
Extreme Ultraviolet Lithography	375	625	5,000	51.6
Maskless Optical Lithography*	0.0	0.0	75	–
Nanoimprint Lithography	50	50	50	0.0

Source: BCC Research

Emerging nanolithographic technologies include a wide range of technologies, of which three (EUVL, maskless optical lithography and nanoimprint lithography) are most likely to have an impact on the market in the years through 2019. The market for these systems, including those sold for R&D purposes, was USD 425 million in 2013 and should reach USD 675 million in 2014, and more than USD 5.1 billion by 2019[354].



Source: BCC Research

Figure 8-17: Global market for developmental nano-tool applications

Case study: EVGroup E. Thallner GmbH

EVGroup E. Thallner GmbH was established in 1980 as an engineering partner for the semiconductor industry (formally known as Electronic Visions) by the entrepreneurs Erich Thallner and his wife Aya Maria Thallner. EV Group expanded into an international manufacturer of highly innovative precision systems. The company is headquartered in St. Florian am Inn, Austria. It has application labs in the United States and Japan.

EV Group E. Thallner GmbH manufactures wafer-bonding, lithography/nanoimprint lithography, metrology, photoresist coating, cleaning, and inspection equipment. It provides CMOS image sensors, high brightness light emitting diodes, wafer level optics, and photovoltaics solutions. The company also offers technical support, spare parts, training, and preventive maintenance services. It delivers advanced packaging, 3D interconnect, compound semiconductor and silicon-based power devices, microelectromechanical systems, nanotechnology, and SOI and engineered substrates to markets worldwide.

[353] Semiconductor Engineering: What Happened To Next-Gen Lithography?, September 3rd, 2014
[354] BCC Research (2014), Nanotechnology: A Realistic Market Assessment p.191

The core products of the company are lithography, bonding and imprint systems. It is one of the key players for all types of wafer bonding equipment, and is one of the market and technology leaders in lithography and nanoimprinting.

Key competencies in lithographic technology lie in the high-throughput contact and proximity exposure capabilities of its mask aligners (EVG600, EVG6000, EVG IQ series) and in its highly integrated coating platform (EVG100 series). All of EVG's lithography equipment platforms are 300mm ready, can be fully integrated into its HERCULES lithography track systems, and are complemented by its metrology tools for top-to-bottom side alignment verification.

With over 15 years' experience in designing and manufacturing precision wafer bonding equipment, EVG wafer bonding systems are well recognised in setting industry standards for the MEMS production industry. Besides supporting wafer level and advanced packaging, 3D interconnects and MEMS fabrication, the EVG500 series wafer bonding systems can be configured for R&D, pilot-line or volume production.

The company's application labs provide equipment demonstrations of its various product portfolios for potential customers looking to leverage EV Group's extensive line up of advanced wafer processing solutions for semiconductor, MEMS and nanotechnology markets. Furthermore, it provides process development support for custom applications to address customer requirements at any stage of the development process. Last but not least, these advanced process development and application labs are designed to accommodate independent research work to explore and develop baseline processes that will open up new market opportunities. This includes working with key partners, like materials suppliers, to develop and optimise new processes and capabilities. EV Group's process development group works with customers needing "demonstrator" parts for their respective customer-specific requirements.

More generally, EV Group E. Thallner GmbH is present across five different markets:

- *Advanced packaging;*
- *Compound semiconductor;*
- *MEMS;*
- *SOI & engineered substrates; and*
- *Nanotechnology.*

Out of these five dynamic markets, nanotechnology seems to be one of the most promising ones for EVG Group.

Nanoimprint Lithography (NIL) is one of the most promising and cost-effective new techniques for generating nanometre-scale-resolution patterns for a variety of commercial applications in BioMEMS, microfluidics, optics, patterned media and electronics.

Nanotechnology applications include:

- *Hot embossing: Hot embossing technology is a low cost, flexible fabrication method, which has demonstrated polymer high aspect ratio microstructures as well as nanoimprinting patterns. It uses polymer substrates to imprint structures created on a master stamp. This allows the stamp to produce many fully patterned substrates using a wide range of materials. Hot embossing is therefore suited to applications from rapid prototyping to high volume production. Hot embossing can be applied in a wide variety of fields: µTAS, microfluidics (micromixers, micro reactors), micro optics (wave guides, switches), etc.*
- *Micro contact printing: An inked stamp transfers a material to a substrate surface by a soft contact, which forms a self-assembled monolayer (SAM). In this method, soft stamps like PDMS are used. The process occurs at room temperature and under low contact forces.*
- *UV-Nanoimprint Lithography: UV-Nanoimprint Lithography (UV-NIL) uses low viscose materials, which are cross-linked during a UV exposure process forming the hard polymer features. These features can be used as the actual device or can be used as an etching mask for pattern transfer in the substrate.*

The average annual revenue of the company is USD 112 million. It employed 700 staff worldwide in 2013, and up to 750 in 2015[355] with 600 at headquarters, 80 in the US and 30 in

[355] Data from Innodys (French distributor for EVG)

Germany. Approximately 100 work on R&D and 20% of revenue is invested in R&D annually.

I HOLOGRAPHIC MEMORY

Holographic memory offers the possibility of storing 1 terabyte (TB)[356] of data in a sugar-cube-sized crystal. Data from more than 1,000 CDs could fit on a holographic memory system. Most computer hard drives only hold 10 to 40 GB of data, a small fraction of what a holographic memory system might hold[357].

In holographic data storage, a laser 'data beam' holding information is crossed with a 'reference beam' to produce an interference pattern that is recorded in a light-sensitive material. To retrieve data from a particular location, a reference beam is shone onto it, and the combination of the reference beam and the patterned material reconstructs the original data beam, which is read by a digital-camera detector that translates the beam into a series of electrical signals. The recording material is typically either an inorganic crystal or a polymer. Polymers are more sensitive and require less powerful lasers, but they have their own flaws. For instance, when photosensitive polymer is impacted by laser light, it tends to deform, corrupting the data[358].

In 2014, a team of researchers from the University of California demonstrated a new type of holographic memory device that could provide unprecedented data storage capacity and data processing capabilities in electronic devices. The memory device uses spin waves – a collective oscillation of spins in magnetic materials – instead of optical beams. Spin waves are advantageous because spin wave devices are compatible with conventional electronic devices and may operate at a much shorter wavelength than optical devices, allowing for smaller electronic devices with greater storage capacity. Experimental results obtained by the team show it is feasible to apply holographic techniques developed in optics to magnetic structures to create a magnonic holographic memory device. The research combines the advantages of the magnetic data storage with the wave-based information transfer[359].

Not all holographic memory technologies are nanoscale. Several promising technologies have been developed by companies such as InPhase Technologies, Colossal Storage and GE Global Research. The Colossal Storage system is apparently the only one that uses nano-photonic technology, in which light interacts with nanoscale structures. In contrast to other holographic technologies, in which the light interacts with the storage medium on a macroscale (> 100 nm) level, the Colossal Storage technology uses a UV laser to write data spots as small as 30 nm in a ferroelectric perovskite thin film[360].

By 2019, sales of nano-devices currently under development, primarily nanostructured holographic memory, are projected to reach USD 50 million[361].

The next section looks at the wider environment for nanotechnology and photonics – regulation and standards, environmental health and safety issues, communication and public attitudes.

[356] A terabyte of data equals 1,000 gigabytes, 1 million megabytes or 1 trillion bytes.
[357] How Stuff Works Tech: How Holographic Memory Will Work,
[358] MIT Technology Review: Holographic Memory, September 1, 2005
[359] University of California, Riverside, UCR Today: Using Holograms to Improve Electronic Devices, February 19, 2014
[360] BCC Research (2014)
[361] Ibid

9 THE WIDER ENVIRONMENT FOR NANOTECHNOLOGY AND PHOTONICS

9.1 Regulation and standards for nanotechnology

9.1.1 European regulations for nanotechnology

In terms of nanotechnology regulation, the European Union is well-advanced but not alone in seeing the need for greater scrutiny on the use of nanotechnologies. To facilitate regulation, *inter alia*, a definition of nanomaterials has been defined by the European Commission in its Recommendation on the Definition of a Nanomaterial - 2011/696/EU. This non-binding document has also been used by other pieces of regulation to define the term 'nanomaterial'. The table below lists some key regulatory documents within the European Union and within Member States.

Table 9-1: Overview of regulations for nanotechnology use in Europe

Status	Name of the document	Country/ Region	Scope	Nano-specific
Implemented	Regulation concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) - 1907/2006(EC)	EU	Chemicals & Raw Materials	No, but 'substance' covers nanomaterials
Implemented	European Commission Recommendation on the Definition of a Nanomaterial	EU	Substances at the Nanoscale	Yes
Implemented	Decree on the annual declaration on substances at nano-scale - 2012-232	France	Substances at the nano-scale}	Yes
Implemented	Royal Decree regarding the Placement on the Market of Substances manufactured at the Nano-scale	Belgium	Substances Manufactured at the Nano-scale	Yes
Implemented	Order on a Register of Mixtures and Articles that contain Nanomaterials as well as the Requirement for Manufacturers and Importers to report to the Register – BEK no. 644	Denmark	Nanomaterials	Yes

Nanotechnology photonics are not regulated *per se*. This discipline is characterised by the wavelength of the emitted light being in the nanoscale rather than the materials used. Nanomaterials used for the realisation of photonic devices are nevertheless regulated under REACH in the EU and other national regulations (see above). Regulations applying to electronics, such as the Waste Electrical and Electronic Equipment Directive (WEEE) - 2012/19/EU and the Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS2) - 2011/65/EU, may also concern electronic devices used for photonics.

9.1.2 Standards for nanotechnology and photonics

The standardisation of photonics is shared amongst several technical committees (TC) of the International Standardisation Organisation. The dedicated ISO/TC for photonics is ISO/TC 172 Optics and photonics. The nanoscale aspects of photonics are however being covered by ISO/TC 229 Nanotechnologies and IEC/TC 113. The twin technical committees develop a joint vocabulary series for nanotechnologies that encompass nano photonics. A technical specification ISO/DTS 80004-10 Nanotechnologies -- Vocabulary -- Part 10: Nano-enabled photonic components and systems is currently under development. Other electronic aspects are covered by IEC/TC 76 Optical radiation safety and laser equipment.

In Europe, the European Standardisation Committee (CEN) has a dedicated technical committee TC 352 that has been working with nanotechnologies. CEN/TC 123 Lasers and photonics and CEN/TC 352 Nanotechnology are responsible for the same issues as mentioned above for ISO. They have however not developed standards relevant to nanotechnology photonics.

The section that follows looks at health and safety.

9.2 Environmental health and safety

Photonics includes the generation, emission, transmission, modulation, signal processing, switching, amplification, and detection/sensing of light. The commercial applications of nanotechnology in the field of photonics include: lasers and parts thereof, nano-engineered photonics materials, communications & all-optical signal processing, and nanoscale functional imaging and spectroscopy. Products for the sector photonics range from communication technology such as Low-Power 100 Gb/s Optical Engine by Mellanox Technologies and Rings of fire by HP to laser devices such as the Comb-Laser by Innolume.

A number of nanoparticles have been identified in the overview of commercially-available products as being used in photonic products (see section on Products in Photonics):

- Gallium nitride nanowires
- Germanium nanoparticles
- Graphene
- Silicon dioxide (silica), crystalline
- Silicon dioxide (silica), synthetic amorphous
- Single-walled carbon nanotube (SWCNT)
- Titanium dioxide (titania, rutile, anatase)

A risk-banding tool called Stoffenmanager Nano[362,363] has been used to prioritise the health risks occurring as a result of respiratory exposure to nanoparticles for the relevant exposure scenarios.

The respiratory route is the main route of exposure for many occupational scenarios, while the oral route of exposure is considered minor and sufficiently covered, from a safety point of view, by good hygiene practices established in production facilities as prescribed through general welfare provisions in national health and safety legislation in EU countries (ECHA 2012)[364]. In view of the nature of the products in this sector, oral exposure of consumers is also considered to be minor.

The dermal route may be the main route of exposure for some substances or exposure situations, and cause local effects on the skin or systemic effects after absorption into the body (ECHA 2012). However, nanoparticles as such are very unlikely to penetrate the skin (Watkinson, et al. 2013), and consequently nano-specific systemic toxicity via the dermal route is improbable. Therefore, when evaluating nano-risks for the respiratory route, the most important aspects of occupational and consumer safety are covered.

9.2.1 Hazard assessment of nanoparticles

In Stoffenmanager Nano, the available hazard information is used to assign specific nanoparticles to one of five hazard bands, labelled A to E (A= low hazard, E= highest hazard). The table below presents an overview of selected nanoparticles of the photonics sector and their hazard bands, either taken from le Feber et al. (2014)[365] or van Duuren et al. (2012), or derived in this project.

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362 Marquart, H., Heussen, H., Le Feber, M., Noy, D., Tielemans, E., Schinkel, J., West, J., Van Der Schaaf, D., 2008. 'Stoffenmanager', a web-based control banding tool using an exposure process model. Ann. Occup. Hyg. 52, 429-441.

363 Van Duuren-Stuurman, B., Vink, S., Verbist, K.J.M., Heussen, H.G.A., Brouwer, D., Kroese, D.E.D., Van Niftrik, M.F.J., Tielemans, E., Fransman, W., 2012. Stoffenmanager Nano version 1.0: a web-based tool for risk prioritization of airborne manufactured nano objects. Ann. Occup. Hyg. 56, 525-541.

364 ECHA, 2012. Chapter R.14: Occupational exposure estimation., in: Anonymous Guidance on Information Requirements and Chemical Safety Assessment., Version: 2.1 ed. European Chemicals Agency, Helsinki, Finland.

365 Le Feber, M., Kroese, E.D., Kuper, C.F., Stockmann-Juvala, H., Hyytinen, E.R., 2014. Pre-assigned hazard bands for commonly used nanoparticles. TNO2014 R11884.

Table 9-2: Hazard bands for selected nanomaterials

Nanoparticles	Hazard Band	Source
Gallium nitride nanowires	E	This report, see Annex
Graphene	E	This report, see Annex
Silicon dioxide (silica), crystalline	E	van Duuren et al. (2012)
Silicon dioxide (silica), synthetic amorphous	C	le Feber et al. (2014)
Single-walled carbon nanotube (SWCNT)	E	This report, see Annex
Titanium dioxide (titania, rutile, anatase)	B	le Feber et al. (2014)

9.2.2 Exposure assessment of nanoparticles

Based on the provided overview of commercially available products, engineered nanomaterials are present in the products as part of a matrix. No free solids or liquids containing engineered nanomaterials, which can become airborne during the use-phase, were listed. During the production of these photonic products, employees can be exposed to free engineered nanomaterials. However, as many of these activities are performed on a R&D scale, exposure to engineered nanomaterials will be relatively low. In conclusion, the use of photonic nano-products results in an exposure band 1 (consumers and workers), whereas during the production of photonic products an exposure band 2 (workers) is believed to be realistic.

9.2.3 Risk assessment of nanoparticles

The hazard and exposure bands are combined to yield so called priority bands, according to the scheme depicted in the table below. A high priority implies that it is urgent to apply exposure control measures or to assess the risks more precisely, and a low priority implies that it is not very urgent to apply exposure control measures ort to establish the risk involved with more precision. It should be emphasised that because of the scarcity of available information, the scheme is set in a conservative way (according to the precautionary principle).

Table 9-3: Priority bands in the Stoffenmanager system

Hazard band / Exposure band	A	B	C	D	E
1	3	3	3	2	1
2	3	3	2	2	1
3	3	2	2	1	1
4	2	1	1	1	1

Key:
Hazard: A = lowest hazard and E = highest hazard;
Exposure: 1 = lowest exposure and 4 = highest exposure;
Overall result: 1 = highest priority and 3 = lowest priority (Van Duuren-Stuurman, et al. 2012)

Risks based on the hazard and exposure banding applied to the sector are listed in the table below. There is a high risk to workers and consumers from gallium nitride nanowires, crystalline silica and single-walled carbon nanotubes, with respect to use and production. Furthermore, there is a moderate risk to workers from amorphous silica and a low risk from the use and production of titania and from the use of amorphous silica and titania.

Table 9-4: Priority bands for nanotechnology photonics

		Exposure Band	
		Production Phase	Use and End-of-life Phase
Nanoparticle	**Hazard Band**	**2**	**1**
Gallium nitride nanowires	E	1	1
Silicon dioxide (silica), synthetic amorphous	C	2	3
Silicon dioxide (silica), crystalline	E	1	1
Single-walled carbon nanotube (SWCNT)	E	1	1
Titanium dioxide (titania, rutile, anatase)	B	3	3

This section on human health and safety: hazard, exposure and risk is presented in much greater detail in the Annex.

The section that follows looks at communication on nanotechnology and photonics.

9.3 Communication, public attitudes and societal issues

9.3.1 Printed and online media

A search on the web of terms related to nanotechnology and keywords related to photonics is summarised in the table below. [366] A second search, using Google Scholar[367], was done in order to obtain an indication of where the interests of academics lie. The ratio of news web-pages to total web-pages for each search was much lower than the ratio of scholarly to general web-pages. Interestingly when American spelling was used, “fibre” as opposed to “fibre”, the news to web ratio was approximately four times higher and the scholar to web ratio was approximately double.

Table 9-5: Frequency of articles on the web and in the news for nanotechnology photonics topics

Keyword Category	Web, '000s	News, '000s	News/Web %	Scholar, '000s	Scholar/Web %
Nanophotonic	275	0.7	0.3	23	8
Photo Optical Instrumentation	496	2.0	0.4	34	7
Silicon Photonic	1,390	8.0	0.6	192	14
Photonic Crystal Fibre	368	2.7	0.7	54	15
Optoelectronic	1,330	1.2	0.1	174	13
Plasmon	859	2.4	0.3	203	24
Polariton	323	1.0	0.3	23	7

There are only a few minor journals specialising in nano-photonics, such as the Journal of

[366] The search was carried out using the keywords listed, coupled with the term “nano*” so all words beginning with nano are included.

[367] Google Scholar is an online database of many of the peer-reviewed online journals of Europe and the US, plus books and non-peer reviewed journals, containing an estimated 160 million documents in 2014 (Orduña-Malea, E.; Ayllón, J.M.; Martín-Martín, A.; Delgado López-Cózar, E. (2014). About the size of Google Scholar: playing the numbers. Granada: EC3 Working Papers, 18: 23 July 2014.)

Nanophotonics (SPIE, USA) and Integrated Photonics Research, Silicon and Nanophotonics (OSA, USA). Most nanophotonics work is published in journals related to the science of materials and interfaces, nanotechnology, physics, physical chemistry, optical materials and optics.

The majority of web-based news articles published on nanophotonics appear on science and technology focused sites such as Nanowerk.com (the top ranked nanotechnology website according to Alexa Internet Inc., a company that measures web traffic) and Phys.org (see figure below). Articles about nanophotonics-based invisibility cloaks dominated the articles related to nanophotonics appearing on mainstream, general interest news websites. News items on invisibility cloaks that refer to "nanometre scale metamaterials" or similar, if they refer to science at all, are about forty times more numerous than those that use the phrase "nanophotonics".[368]

Being under-reported in general interest news is likely due to the complexity of the underlying physical principles and technical nature of the real-world applications of nanophotonics, which include lighting, sensors, optical amplifiers and photovoltaic cells. This is the opposite to, for example, nanotechnology related to cancer treatment where the relevance and impact on the general public is much clearer and straightforward to explain. If the nanophotonic phenomena of structural colour became mainstream in the future, its use in textiles would be an example of nanophotonics the public could relate to better.

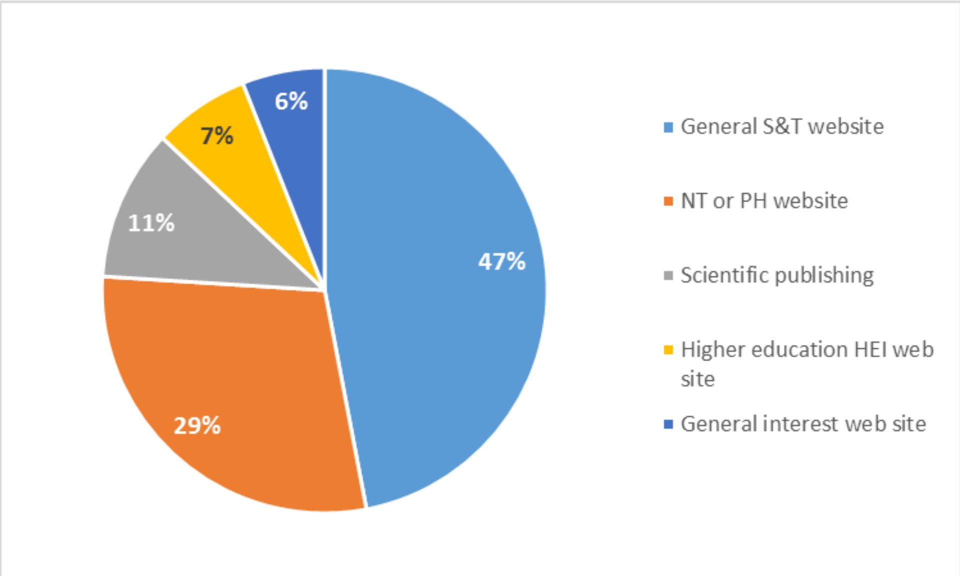

Figure 9-1: Type of website for top 100 news items found using Google and the search term 'nanophotonics' June 29, 2015

The number of google scholar listings for the search term "nanophotonics" has increased linearly over the last decade, as shown in the figure below.

[368] Number of news items found by a google search of "invisibility cloak" nanophotonic (117) compared to "invisibility cloak" (4710) on 29/06/2015.

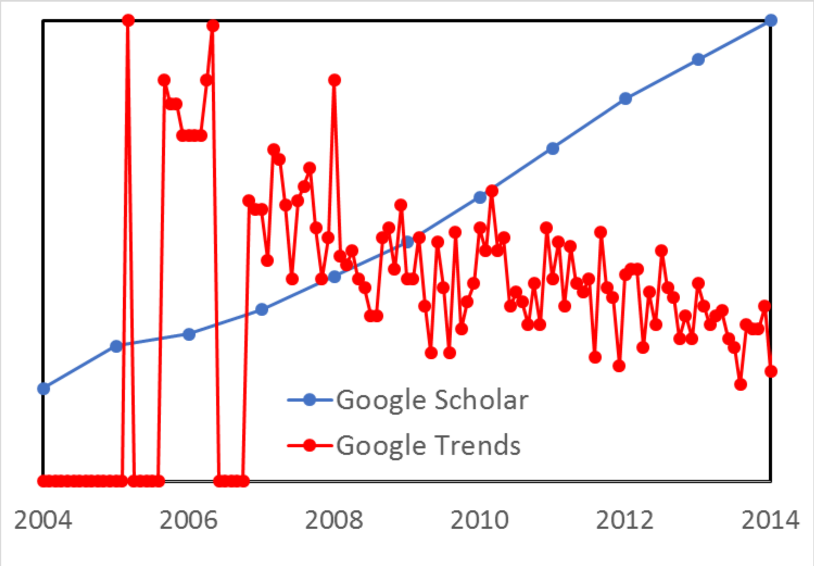

Figure 9-2: Normalised web trends for the search term 'nanophotonics'
Google Scholar was used to chart academic interest and Google trends to chart general interest on the web.

This does not mean that the amount of nanophotonics work follows the same trend, because the popularity of the term "nanophotonics" could just have increased within the scientific community. Over the same period of time the term "optoelectronics" peaked in 2011 before decreasing 20% by 2014. Opposite to what was seen in the search of academic literature, the popularity of the term "nanophotonics" on the whole web has decreased in recent years.

More than 200 scientific journals regularly publish articles on nanotechnology[369]. For the academic community, the International Scientific Journal & Country Ranking (SJR) index provides a means of identifying which are perceived to be the most prestigious. The h-5 index is a measure of the number of highly cited articles, and is thus dependent on how many articles are published annually by the journal. The top five journals, as measured by the SJR index largely follows the metric of citations per document published, as shown in the table below.

Table 9-6: Bibliometric data for nanotechnology

Title of journal	SJR	h-5 index 2010-14	Total articles (3 years)	Citations per article (2 years)	Country
Nature Nanotechnology	17.0	140	626	23.8	UK
Nano Letters	9.4	181	2940	13.2	US
Advanced Materials	7.9	190	2511	15.2	DE
Nano Today	7.8	61	195	17.4	NL
ACS Nano	7.0	170	3387	12.0	US

Source: http://www.scimagojr.com/journalrank.php?category=2509

While it should be noted that many nanotechnology publications may not have a Facebook page, one indication of popularity of nanotechnology media can be seen in the figures for the number of "Likes" on Facebook:

[369] http://www.nanowerk.com/nanotechnology/nanotechnology_periodicals.php

Table 9-7: Facebook likes as a measure of interest in nanotechnology

Facebook Page	Likes
Nanotechnology	99,000
Nanotechnology World Association	33,000
Nanotechnology Now	6,400
Nanotechnology Solutions	3,500
Nanowerk Media/News/Publishing	5,400
The International Nano Science Community	5,700
Nanobiotechnology	2,100

This information may be useful in targeting any information for the public in future over and above the EC's own web pages.

9.3.2 Surveys of the public

More rigorous measures of public awareness, attitudes and communication can be seen through surveys but public surveys on nanomedicine have been scarce so far. Although not representative for the 'average' EU-citizen, the results provide some indications of trends in attitudes.

NanOpinion was an FP7 project, which ran from 2012 to 2014, focused on monitoring public opinion on nanotechnology in Europe[370]. An online hub, social media, education and information booths in public spaces and special events were used to develop a dialogue with the general public about nanotechnology. Over 1,500 questionnaires were completed in which participants answered questions designed to gauge their understanding and opinions of nanotechnology.

Analysis of the questionnaires revealed that Europeans in general have little understanding of nanotechnology but are generally interested in and positive about it. Respondents expected information on nanotechnology to be honest and balanced and wished there was more information available, particularly in the popular media. Across all educational backgrounds, they would be interested in buying products, including food containers, clothing and sun cream, containing nanomaterials. However, they would like to see nano-containing products labelled with detailed information and the testing and regulation of these products carried out by independent national or international bodies rather than profit-oriented companies. Their main policy recommendations were to promote consistent and detailed product labelling carried out by an independent body, to update teachers' knowledge of nanotechnology and to encourage more interdisciplinary STEM (science, technology, engineering and mathematics) curricula.

The objectives of NanoDiode, an FP7 project running from mid-2013 to mid-2016, is to develop a co-ordinated and innovative strategy to engage EU civil society in a dialogue about responsibility around nanotechnologies[371]. As part of their approach they reviewed the experiences and outputs of previous European projects on nanotechnology dialogue and outreach in order to identify best practices they could adopt for educational workshops and other activities[372]. The scope of NanoDiode is more ambitious than NanOpinion in as much as they aim to facilitate dialogue across all levels of the nanotechnology value chain, from the general public to policy makers. Through outreach, education and specific events they will involve a cross-section of researchers, industrialists, citizens, scientific advisers and policy makers with the aim of learning where and how society wish nanotechnologies to be applied. For example, they aim to bring groups of potential nanotechnology 'users' (industrial customers as well as consumers) together with researchers working on near-market products to facilitate discussions which could help steer the research towards social values and user needs.

In addition to these FP7 projects, two population surveys in Germany provide some data on the public's attitudes, with a few results relevant for nanomedicine (Zimmer et al, 2009)[373], as well as a

[370] www.nanopinion.eu
[371] www.nanodiode.eu
[372] Analysing previous experiences and European projects on nanotechnology outreach and dialogue and identifying best practices, Daan Schuurbiers and De Proeffabriek, March 2014, (Accessed at http://www.proeffabriek.nl/uploads/media/NanoDiode_WP1_Best_Practices.pdf in November 2015)
[373] Zimmer, R., Hertel, R., Böl, G.F., 2009, "Public perceptions about nanotechnology: Representative survey and basic morphological-psychological study", Bundesinstitut für Risikobewertung (BfR)

survey among young people conducted within the framework of the NANOYOU project (NANOYOU, 2010)[374] and a recent survey in the USA (Shipman, 2010)[375]. Work has also been undertaken by the OECD on public engagement with nanotechnology and a guide produced to assist policymakers working with the public on issues related to nanotechnology (OECD, 2010)[376].

Relatively favourable situations may exist if citizens have concrete experiences with, or expectations towards specific applications; they tend to support applications "that are linked to a wider social good or perceived individual benefit" (Böl, 2010; Fleischer et al., 2012)[377,378]. This may very well be the case for medical and especially for cancer therapy applications.

Table 9-8: Assessments by the public of various applications of nanotechnology
From German online discourses and a questionnaire survey (Böl et al. 2010)

Application	Ratio of Positive to Negative Assessments	
	Online Discourses	Population Survey
Cancer therapies	90 : 10	(not asked)
"Other serious medical applications"	88 : 12	87 : 13
Surface treatment (textile & vehicle)	67 : 33	93 : 7 (paints) 91 : 9 (textile)
Cosmetics (excl. sunscreens)	59 : 41	51 : 49
Textile; other than surface treatment	56 : 44	76 : 24
Food packaging	25 : 75	81 : 19 (detection) 64 : 36 (foil quality)
Foodstuffs	10 : 90	25 : 75 (lump prevention) 10 : 90 (appearance)
Sunscreen products	10 : 90	78 : 22
Dietary supplements	0 : 100	not asked

In approximately 50% of the postings relating to medical applications, mainly benefits were expected, while in only 5% of the postings mainly "harm" was expected (Böl, 2010). In the most recent years analysed - 2007 and 2008 - an increase in the fraction of positive assessments of medical applications was seen.

In another recent survey in the USA, 849 respondents were included, and it appeared that "support for therapeutic applications of nanotechnology was strong, while support for human enhancement applications much less" (Shipman, 2010).

374 Nanoyou, 2010 http://cordis.europa.eu/publication/rcn/15319_fr.html
375 Shipman, M., 2010, "Hiding risks can hurt public support for nanotechnology", News Services of the North Carolina State University
376 http://www.oecd.org/sti/biotech/49961768.pdf
377 Böl, G.F., Epp A., Hertel, R., 2010, "Perception of nanotechnology in internet-based discussions", Bundesinstitut für Risikobewertung (BfR)
378 Fleischer, T., Jahnel J., Seitz S.B., 2012, "NanoSafety – Risk governance of manufactured nanoparticles", European Commission

10 CONCLUDING SUMMARY

Photonics is universally being developed for and used throughout manufacturing and a wide range of research and commercial applications. It has importance, for example, in health, energy and ICT. The support being provided for nanotechnology photonics is therefore distributed among many sectors and applications. Thus, there are many avenues through which researchers are being supported to produce publications and engage in projects that increase knowledge and the number of patents and commercialised products based on nanotechnology photonics.

Throughout Framework Programme projects, publications and patents, it is seen that researchers, organisations and companies from a small number of countries prevail. For the EU28, actors in Germany, the United Kingdom and France lead the way, Italy, Spain and the Netherlands being in a second highly-productive group. This reflects in part the size of the countries, the size and strength of their research bases and their ability to fund research and development at a large scale. Organisations in those and other countries (e.g. Denmark and Sweden) are among the strongest in publications in the EU countries, as is the Swiss institutions EFPL. Companies are less prolific publishers with the higher numbers of publications (28 being the highest from any one corporation) coming from large international corporations (IBM, NTT, Samsung).

Looking at the trend in numbers, about 86,000 publications on nanotechnology photonics have been found over the period 2000-2014, an average of 5,700 per annum and c. 5 % of the total output for nanotechnology of 1.8 million publications. In a similar period, approximately 658 patent applications were filed at the European Patent Office and 1,693 at the US Patent Office (USPTO).

There are indications that the relevance of photonics has increased between FP6 and FP7 and that nanotechnology photonics activity is rather more oriented towards basic research than development and the market place. There are several significant initiatives in the European context, amongst them the European Technology Platform Photonics21; the ERA-NET ERASPOT (Strengthening Photonics and Optical Technologies for Europe); the ERANETplus actions under FP7: PIANO+, OLAE+ and BiophotonicsPlus; and the Network of Excellence PHOTONICS4LIFE.

The majority of commercialised products using nanotechnology for photonics are in the application areas of advanced lighting, screens and displays, and other optical applications, as well as electronics for the scanning, sensing and imaging systems and for data transmission, storage and communication. Nanotechnology is particularly important in photonics in photovoltaics (PV or solar cells), light emitting diodes (LEDs), organic light emitting diodes (OLEDs) and near field optics. Applications include nano-coatings and thin films (for lenses, optical fibre cladding, etc.); thin films (for optical recording media and light-emitting diodes LEDs, etc.); and nanotools (such as microscopes and lithographic tools). New application areas are expected through the further use of quantum dots, carbon nanotubes and graphene, in particular, in addition to longer-term possibilities (based on electron spin, such as spintronics).

Global sales for nanotechnology products in the photonics sector are forecast to be over USD 29 billion in 2019, 80% of the growth based on already existing application areas.

ANNEXES

ANNEX 1: METHODOLOGIES FOR LANDSCAPE COMPILATION REPORTS

The outline of this report is as follows:

- Introduction;
- Development of keywords;
- Methodology by task and sector: projects, publications, patents and products;
- Methodology for additional information: markets, wider economic data, environmental health and safety, regulation and standards; and
- Concluding remarks.

A Introduction

This paper outlines the main methodologies used in the NanoData project.

The data were in large part identified using keywords to search existing databases (e.g. for publications and patents) and to select projects (from eCorda) and products (e.g. from product databases). The report explains how the keywords were identified and what quality control measures were put in place.

It should be noted that eight sectors were included in the work – construction, energy, environment health, ICT, photonics, manufacturing and transport. Thus, the data are not comprehensive across all of nanotechnology. They are, instead, representative of the sectors selected within the context of the overall project for the European Commission.

B Development of keywords

The keywords were identified from known data sources, web searches and expert input. They were validated through discussions with consortium members[379] (where they had expertise and experience in the area concerned) and other experts. Following that validation process, the keywords were also tested by one or both of the following methods:

- The word 'nano' and the keywords were used to select the FP projects relevant to the sector (and sub-sectors if appropriate). The projects identified were checked manually for false positives. False negatives were also identified (projects that were expected to be selected that were not). The keywords were refined to optimise the number of projects correctly selected.
- The keywords were used to select publications. The lists of publications were checked, in part manually and in part semi-automatically using the CWTS VOSViewer bibliometric mapping tool (http://www.vosviewer.com/Home). Using the tool, it was possible to see how terms group together in publication space (by their proximity on a VOSViewer map) and how often they occur (by their size on the VOSViewer map). Thus, it was possible to determine which terms would be the most significant in the sector and also which terms would be likely to cause false positives. For example, in the partial map for nanotechnology and health below (bottom left corner) it can be seen that a very important term is 'scaffold', and related terms are about tissue and bone engineering. Moving further to the right, the related term 'biocompatibility' is seen and nearby the significant and related but more generic terms 'surface', 'morphology' and 'synthesis'.

379 Partners of the Joint Institute for Innovation Policy for this project i.e. CWTS, Frost & Sullivan, Joanneum Research, Oakdene Hollins, the Nanotechnology Industries Association, Tecnalia and TNO.

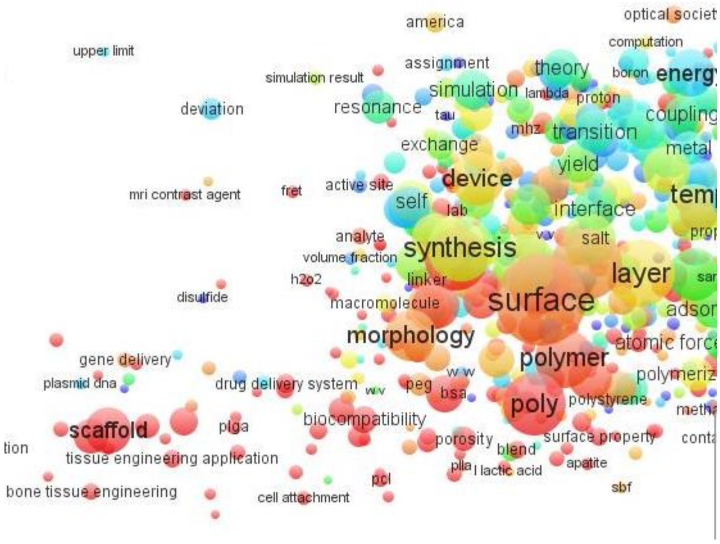

Figure A: Partial VOSViewer map for nanotechnology and health

Additional terms could also be identified for inclusion in the keyword list.

It should be noted that, where the use of a keyword could lead to false results, the keyword was omitted. This inevitably leads to some data of relevance being omitted from the resource base of the project, the alternative being the inclusion of much irrelevant information. For example, some words (e.g. photodetector, laser, photolithography) were omitted from the keywords for photonics as they have much wider applications that photonics alone.

In the searches, keywords were truncated to maximise the possible results. For example, in energy, “thermoelectric*” could identify data related to “thermoelectric”, “thermoelectrics”, “thermoelectrical” and “thermoelectricity”, the * indicating the truncation.

Where possible, both British and American spellings were included (e.g. tumour and tumor) as were alternative spellings (e.g. orthopaedic and orthopedic).

Methodology by task and sector

C Framework Programme projects

The Framework Programme (FP) project details were provided by the European Commission from the eCorda database for FP6 and FP7. Abstracts for the FP6 projects were provided separately as these were not in the original database received. The total number of FP projects in eCorda database is 35,365 of which 25,238 are FP7 projects and 10,027 FP6 projects. These projects involved 210,177 participations by researchers of which 76,562 are in FP6 and 133,615 in FP7.

The table below presents an overview of the data for FP6 and FP7 according to the variables used in the NanoData analysis. It also identified the number of missing values per variable. It shows that the eCorda database is a nearly complete source of FP6 and FP7 project data and participant data with only relatively few data missing (between 2.4% and 0% of the total for FP6 and FP7 depending on the variable).

Table A: Number of actual observations and missing values for each of the eCorda variables used for the NanoData analysis.

Variable	Number of observations						
	FP6		FP7		Total		
	Actual	Missing	Actual	Missing	Actual	Missing	% Missing
Project ID	10,027	0	25,238	0	35,265	0	0.0%
Start date	9,966	61	24,906	332	34,872	393	1.1%
End date	9,965	62	24,906	332	34,871	394	1.1%
Duration	10,027	0	25,238	0	35,265	0	0.0%
Number of partners	10,027	0	25,238	0	35,265	0	0.0%
Specific Programme	10,027	0	25,238	0	35,265	0	0.0%
Sub-Programme[380]	10,027	0	25,238	0	35,265	0	0.0%
Call	9,989	38	25,238	0	35,227	38	0.1%
Instrument	1,0027	0	25,238	0	35,265	0	0.0%
EC contribution	10,027	0	25,238	0	35,265	0	0.0%
Project total cost	9,771	256	25,238	0	35,009	256	0.7%
Project ID	76,562	0	133,615	0	210,177	0	0.0%
Participant ID	76,550	12	133,615	0	210,165	12	0.0%
Participant role	76,562	0	133,615	0	210,177	0	0.0%
Participant legal name	76,561	1	133,615	0	210,176	1	0.0%
Participant country[381]	76,562	0	133,615	0	210,177	0	0.0%
Participant region	76,562	0	133,615	0	210,177	0	0.0%
Participant organisation type	74,271	2,291	133,615	0	207,886	2,291	1.1%
EC contribution per participant	71,748	4,814	133,569	46	205,317	4,860	2.4%
Project cost per participant	72,960	3,602	133,575	40	206,535	3,642	1.8%

In the eCorda database, the EC contribution per project shows some small differences between the data presented by project (project database) and the data presented by participant (participant database). The table below illustrates the differences, both in millions of euros and as shares of the EC contribution. It can be seen that the difference in EC contribution between the project and participant data is almost zero in FP7 and small in FP6. However, the differences can become significant when the data is aggregated.

[380] In FP6 these were called Priorities and in FP7 Work Programmes.
[381] The report uses ISO 2-digit codes for countries. See http://www.iso.org/iso/country_codes

Table B: Number of projects and EC contribution for the project data and participant data in eCorda

	Number of projects		EC contribution (MEUR)		Difference (Project – Participant) (MEUR)	Difference %
	Project Data	Participant Data	Project Data	Participant Data		
FP						
FP6	10,027	10,027	16,692.320	16,653.860	38.460	0.23%
FP7	25,238	25,238	44,917.330	44,917.200	0.130	0.00%
Total	35,265	35,265	61,609.650	61,571.060	38.600	0.06%
NT						
NT-FP6	908	908	1,702.740	1,695.500	7.250	0.43%
NT-FP7	2,636	2,636	4,660.840	4,660.750	0.090	0.00%
Total	3,544	3,544	6,363.580	6,356.250	7.340	0.12%

C1 Classification of projects

C1.1 Classification of nanotechnology projects

In order to identify the baseline set of nanotechnology-related projects for the NanoData work, a search was made for all FP projects that contained 'nano'[382] in the title or abstract of the project. 3,544 projects were selected in this way[383], of which 74% were FP7 projects and 26% were FP6 projects. Comparing the distribution of projects between FP6 and FP7 for nanotechnology and for the two FPs overall, it is found that the distributions are very similar the latter being 72% in FP7 and 28% in FP6. Nanotechnology projects make up 10% of Framework Programme projects, the share increasing slightly from FP6 (9.1%) to FP7 (10.4%).

The table below shows the distribution of total FP projects and of nanotechnology projects.

[382] The term "nano" could appear as a part of a word (e.g. nanotechnology, nanoscience, nanomaterial, nanoscale), as a part of compound word separated with hyphen (e.g. nano-science) or as an independent word "nano".

[383] Unlike the other sectors considered by the project (HT, EN, PH, MF), for ICT additional projects were identified by use of keywords such as graphene. These were judged to be too important in ICT to be omitted. This did, however, result in the total number of nanotechnology projects being different for ICT (4,143) and the other sectors (3,544).

Table C: Number and share of nanotechnology projects in FP6 and FP7

		Total	FP7	FP6
FP total	Number of FP projects	35,265	25,238	10,027
	Share of FP (total)	100%	71.6%	28.4%
Nanotechnology	Number of FP projects	3,544	2,636	908
	Share of FP	100%	74.4%	25.6%
Share of nanotechnology of total FP		10.0%	10.4%	9.1%

C1.2 Classification of projects by sector and sub-sector

The 3,544 projects relevant to nanotechnology were subjected to a search using the sector keywords to identify projects relevant to each sector. This search was undertaken using the keywords identified for each sector. The project details for the selected projects were reviewed manually, where possible, as a further check of the quality of the outputs of the keyword search process.

For example, using the method described above, 944 projects were categorised as being related to nanotechnology and health, approximately 27% of total nanotechnology projects. Using the keywords identified for each of the five health sub-sectors[384], a further classification could be made. In addition, nanotechnology projects relevant to health but not specifically to any of the five sub-sectors were categorised as Other. In this way, the breakdown of health nanotechnology projects was found to be: cancer 26% (CT); infectious diseases 7.8% (ID); cardiovascular diseases 5.2% (CV); neurodegenerative diseases 4.6% (ND); and diabetes (2.2%) (DB) with Other being 62% (OTH).

Where projects were classified as belonging to more than one sub-sector, a proportion of each such project was allocated to the sub-sector concerned. Thus a project relevant to cardiovascular disease and cancer would be allocated 50% to cardiovascular disease and 50% to cancer. The aim was to ensure an accurate analysis of the FP project data and to minimise double counting. The table that follows shows the number of project overlaps and the distributions of fractions of projects for the health sub-sectors.

[384] Cancer, cardiovascular disease, diabetes, infectious diseases and neurodegenerative diseases.

Table D: Distribution of projects with overlaps across health sub-sectors

	Total	CT	CV	ID	NE	DB	Other
Projects without overlaps	**883**	**196**	**23**	**48**	**24**	**11**	**581**
Projects with overlaps: fractions as allocated							
CT & ID	17	8.5		8.5			
CT & CV	12	6	6				
CT & ND	9	4.5			4.5		
CV & ID	5		2.5	2.5			
CV & ND	4		2		2		
CT & DB	4	2				2	
CV & DB	3		1.5			1.5	
ND & DB	2				1	1	
CT, ID & ND	1	0.33		0.33	0.33		
CT, ND & DB	1	0.33			0.33	0.33	
CT, CV & ID	1	0.33	0.33	0.33			
CT, CV, ID & ND	1	0.25	0.25	0.25	0.25		
ID & ND	1			0.5	0.5		
Sum of fractions	*61*	*22*	13	12	9	5	0
Total nanotechnology and health	**944**	**218**	**36**	**60**	**33**	**16**	**581**

C2 Harmonisation of data across FP6 and FP7

In order to have harmonised variables across both Framework Programmes, some names and coding of variables were required. These included the following:

i) Harmonising the participant types. The categories used in this report are presented in the table below. In the tables of top performers, if the same organisation appeared in FP6 and FP7, the FP7 code was used.

Table E: Harmonising participant type codes

Codes used	Description	FP6 Code	FP7 Code
HES	Higher or secondary education establishment	HES	HES
REC	Research organisations	REC	REC
PRC	Private commercial (excluding SMEs)	IND	PRC
SME	Small and medium-sized enterprises	SME	SME
OTH	Other including public bodies excluding research and education	OTH	OTH, PUB

ii) Introducing a classification of instruments in order to allow enhanced comparison between the varieties of instruments. The categorisation follows that of Arnold et. al (2012)[385].

[385] In their work Arnold et. al. (2012) Understanding the Long Term Impact of the Framework Programme classifies the instruments of FP4, FP5 and FP6 into four categories that are used as guidance for our classification. For FP7 the classification is done by authors of this report.

Table F: Classification of instruments

Action	Instrument	FP
Research actions	ERC Grants	FP7
Collaborative RTD actions	Integrated Projects	FP6
	Specific Targeted Research Projects	FP6
	Large-scale Integrating Project	FP7
	Small or medium-scale focused research project	FP7
	Integrating Activities / e-Infrastructures	FP7
	Collaborative project (generic)	FP7
Actions for RTD knowledge transfer	Specific Actions to Promote Research Infrastructures	FP6
	Marie Curie Actions	FP6
	Coordination Actions	FP6
	Network of Excellence	FP6
	Coordinating Action	FP7
	Marie Curie Actions	FP7
	Research Infrastructure	FP7
	Collaborative project dedicated to international cooperation partner countries (SICA)	FP7
Actions for adoption and innovation	Co-operative Research Projects	FP6
	Collective Research Projects	FP6
	Joint Technology Initiatives	FP7
	Research for SMEs	FP7
Actions to support policymaking	Specific Support Actions	FP6
	Supporting Action	FP7

iii) Participant organisations identifiers

For the FP6 and FP7 participants the following organisation identifiers were used:

- FP7: CD_ORG_ID and
- FP6: Participant Identifying Code-PIC.

If these were not available, the programme participant identifiers were used. In order to improve the comparability of the FP6 and FP7 participant identifiers, some manual matching based on organisation legal name and address data was conducted for the NT participant sample. As a result, 5,945 unique nanotechnology participants were identified.

C3 Treatment of decimals

As a general rule, the data in the tables and figures are produced by utilising the method of first summing the unrounded figures and then rounding the sum. Due to this process, some totals may not correspond with the sum of the separate figures (generally presented as limited to one decimal).

C4 Key terminology and abbreviations used

Table G: FP6 funding instrument types

Code	FP6 Type of instrument
STREP	Specific Targeted Research Projects
CA	Coordination Actions

SSA	Specific Support Actions
II	Specific Actions to Promote Research Infrastructures
IP	Integrated Projects
NOE	Networks of Excellence
MCA	Marie Curie Actions
CRAFT	Co-operative Research Projects
CLR	Collective Research Projects
I3	Specific Actions to Promote Research Infrastructures

Table H: FP7 funding instrument types

Code	FP7 Type of instrument
CP	Collaborative project
ERC	Support for frontier research (European Research Council)
MC	Support for training and career development of researchers (Marie Curie)
JTI/169	Activities under Article 169 or 171 European Treaty, Joint Technology Initiatives, Public Private Partnerships
CSA	Coordination and support action
BSG	Research for the benefit of specific groups
NOE	Network of Excellence

Table I: Organisation types

Code	Description
HES	Higher or secondary education est.
PCO	Private companies excluding SMEs
REC	Research organisations
SME	Small and medium-sized enterprises
OTH	Other (incl. public bodies and bodies with unknown organisation types)

Table J: Country codes EU28+[386].

NUTS0	Country		NUTS0	Country
AT	Austria		**LU**	Luxembourg
BE	Belgium		**LV**	Latvia
BG	Bulgaria		**MT**	Malta
CY	Cyprus		**NL**	Netherlands
CZ	Czech Republic		**PL**	Poland
DE	Germany		**PT**	Portugal
DK	Denmark		**RO**	Romania
EE	Estonia		**SE**	Sweden
ES	Spain		**SI**	Slovenia
FI	Finland		**SK**	Slovakia
FR	France		**UK**[387]	United Kingdom
EL[388]	Greece		**CH**	Switzerland
HU	Hungary		**IL**	Israel
HR	Croatia		**IS**	Iceland
IE	Ireland		**TR**	Turkey
IT	Italy		**NO**	Norway
LT	Lithuania		**ZK**	Macedonia

D Publications

Identification of publications relied on analysis of the data in the database at CWTS (the Centre for Science and Technology Studies, Leiden University, the Netherlands), data that is based on that in the Web of Science[389].

The CWTS database is organised and structured such that it allows (dynamic) field delineation and the collection of relevant publications. Hence it was possible to identify nanoscience and nanotechnology (NST) publications and, within those, to identify publications relevant to the sectors. More specifically, publications were sought within the NST group using the keywords. In addition, using the tools available at CWTS, related publications could be identified and included in the output.

Data available from the resource at CWTS included the journals in which the publications are found, the date of publication and the doi (digital object identifier). For licensing reasons, some of the data in the database at Leiden can be accessed by external parties only in aggregate form. For example, personal details of individual researchers cannot be accessed (e.g. address, email, phone number).

The report uses ISO 2-digit codes for countries. See http://www.iso.org/iso/country_codes

E Patents

[386] Data was also analysed from countries outside of the EU28 namely Iceland (IS), Israel (IL), Norway (NO), Switzerland (CH) and Turkey (TR).
[387] GB is also used
[388] GR is also used
[389] http://thomsonreuters.com/en/products-services/scholarly-scientific-research/scholarly-search-and-discovery/web-of-science.html

The patents analysed were collected from the database PATSTAT. That database includes patents from over 30 patent offices e.g. the European Patent Office, the US Patent Office and the Japanese Patent Office.

All patent offices worldwide tag nanotechnology-related patent applications using a special symbol of the International Patent Classification (IPC), namely B82Y. This special symbol is also part of the CPC (Co-operative Patent Classification). The core dataset of nano-related patents were selected using this special symbol (B82Y) from both the IPC and the CPC classifications.

All patent applications at the USPTO, the EPO and PCT (WIPO) classified as B82Y were identified in PATSTAT as well as the (simple) patent family to which they belong. From all these patent families, only patent applications at the USPTO, the EPO and PCT (WIPO) were collected. Such use of multiple patent offices helps to diminish the bias that might be caused by the so called 'home advantage' effect, i.e. the propensity of nationals to file the first patent application in their own country. By analysing across these three patent authorities a less biased overview of nanotechnology patents worldwide can be obtained.

As the patent information is being collected from more than one patent authority, and given that the same invention might be protected in more than one of these patents authorities, the (simple) patent families are used to avoid multiple counting of the same invention.

The identification of patents by sector from amongst the nanotechnology patents was based in most cases on the combination of two strategies. First, all patents including in their title and/or abstract at least one relevant keywords for a particular sector were retrieved. Second, to ensure that the patents retrieved in the first step are truly related to the sector, a number of representative IPC symbols of the sector were selected from PATSTAT[390]. For example, for the nanotechnology patents related to the health sector, the IPC symbols related to 'Pharmaceuticals' and 'Medical technology' were used. However, it was not possible to undertake this second step for all sectors as for some (e.g. manufacturing) there were no appropriate IPC symbols.

Organisations and/or individuals are listed in patent applications, these being applicants and/or inventors. This information is used in the identification of companies, universities and other research organisations active in patenting. The year of reference used is the year when the oldest priority of each patent family was applied (the closest date to the invention). The report uses ISO 2-digit codes[391] for countries.

F Products

Products were identified primarily through keyword, sector and sub-sector searches of reports and databases. This search strategy was based on a triangulation approach making use of complementing perspectives. For all perspectives the NanoData team made use of the sector specific lists of key words.

The first step was to use peer-reviewed and grey literature on products in the different sectors[392] as well as existing market reports[393]. The market reports were used to identify where nanotechnology is being applied already in products as there are many reports that appear to identify products but no product is for sale at a commercial level, being at the research stage or for very limited supply e.g. to the research community or for test purposes. These investigations were then complemented by querying web-based databases on nanotechnology products such as AZONANO[394], Nanowerk[395], the consumer products inventory of the Project on Emerging Nanotechnologies[396], the product database of understandingnano.com[397], the Nanoinformationsportal of the Österreichische Agentur

[390] PATSTAT also contains a table mapping 44 industrial sectors and the IPC classification. The linkage between technology areas and industrial sector is described in Schmoch et al (2003), "Linking Technology Areas to Industrial Sectors", final report to the European Commission, DG Research.
[391] http://www.iso.org/iso/country_codes
[392] E.g. Nanomedicine: Nanotechnology, Biology, and Medicine 9 (2013) 1–14, Hessen Nanotech (2008) Applications of Nanotechnologies in the Energy Sector.
[393] See BCC Research www.bbcresearch.com
[394] http://www.azonano.com/
[395] http://www.nanowerk.com/
[396] http://www.nanotechproject.org/cpi/
[397] http://www.understandingnano.com/nanotechnology-product-suppliers.html

für Gesundheit und Ernährungssicherheit GmbH[398], the Danish Inventory of Nanoproducts[399] and the nanowatch.de database[400]. Further sector-specific databases, such as the German database for medical practitioners and the database on European public assessment reports of the European Medicines Agency[401], were used for the identification and classification of nanotechnology related products in health, for example.

By querying databases on existing innovation policy projects, initiatives and industry platforms such as NANORA[402], the Nano-Map of the German Federal Ministry of Research[403], the database on photonic companies compiled by EPIC, the members directory of SEMI[404], and the Nano-Bio Manufacturing Consortium (USA)[405], additional enterprises active in nanotechnology sectors were identified.

A third perspective on products was developed by gathering additional information about the products from company websites identified in previous work, commercial databases and open sources of information on the web. The information was verified through additional searches (e.g. of product data sheets and company websites).

The information in the database was extensively verified. Where, for example, it was found that a product was identified but not verified, searches were made of sources including reports and company websites to check the information. Contact was also made, in some cases, directly with the company in order to ratify the existence on the market of the product. While some other databases actually state the level of known accuracy of their information (e.g. the entries in the Woodrow Wilson database are classified using a system that has categories from level 1 (extensively verified claim) to level 5 (not advertised by manufacturer – claims made only by third party)) others are not specific.

In NanoData, the aim is only to include products that can be verified.

G Other information

Several types of information are provided on the NanoData site as fixed text where data is limited or one-off. These include information on markets and wider economic data, as well as reports on environmental health and safety and information about regulation and standards.

Markets

The market data is based on available sources of information and sources of Frost & Sullivan and BCC Research, who gather their information through discussions with practitioners (e.g. company representatives) and open sources (e.g. commercial reports, web sites). The aim was to track, evaluate and measure the activities of major industry participants in the nanotechnology arena, looking at markets and usage of nanotechnology. The activities included the definition and specification of nano-materials and nano-enabled products, identification of current and upcoming products and applications, accumulating qualitative and quantitative data, identification and mapping of EU participants and last but not the least, identification and analysis of target markets.

A wide set of definitions, categorisations, data collection and forecasting methods were available. Data gathering was driven by experienced analysts and based on a data-rich portfolio of previous EU and OECD projects as well as on internal Frost & Sullivan databases and consortium members, and public database. European Patent Office[406], PRODCOM[407] and patentlens[408] databases could be used to provide in-depth information about a particular technology and to identify the key industry participants dominating the sector. Analysis of key value chains was undertaken and corroborated with other work-streams. The information thus acquired would be verified with the help of an array

[398] http://nanoinformation.at/produkte.html
[399] http://nanodb.dk/
[400] http://www.bund.net/nc/themen_und_projekte/nanotechnologie/nanoproduktdatenbank/
[401] http://www.ema.europa.eu/
[402] http://www.nanora.eu/
[403] http://www.werkstofftechnologien.de/en/
[404] http://www.semi.org/en/Membership/MemberDirectory/
[405] http://www.nbmc.org/members-only/
[406] https://www.epo.org/searching.html
[407] http://ec.europa.eu/eurostat/web/prodcom
[408] https://www.lens.org/lens/search?n=10&q=nanotechnology&p=0

of primary interviews with leading technology researchers, industry experts and other active stakeholders.

The range of primary and secondary research processes would be followed by the application of innovation diffusion tools in order to forecast probable market scenario of the future. This would also include estimating the shape of the diffusion curve and prediction of market development of nano-enabled products.

Wider economic data

External information sources such as Eurostat, OECD and WHO data sources were used to put the nanotechnology data obtained in the project into context.

For example:

- A brief overview of the energy industry was based on Eurostat data.
- The health industry overview was based on Eurostat data supplemented by reports from industry organisations (both technical (e.g. the industry association for European pharmaceutical enterprises) and financial (e.g. the European Private Equity & Venture Capital Association))

While reports on industry as a whole were available, there were found to be very few reliable reports on nanotechnology and industry. Nanotechnology databases were also explored (e.g. those of Nanowerk and Nanora).

Environmental health and safety

For the sectors in which materials were the main focus, the tool used for the environmental health and safety evaluation was the "Stoffenmanager Nano" application[409]. In summary, Stoffenmanager Nano is a risk-banding tool developed for employers and employees to prioritise health risks occurring as a result of respiratory exposure to nanoparticles for a broad range of worker scenarios. In the absence of a comparable tool for consumer exposure, it was also used for this type of exposure. Stoffenmanager Nano combines the available hazard information of a substance with a qualitative estimate of potential for inhalation exposure. Stoffenmanager Nano does not consider dermal and oral routes of exposure.

In Stoffenmanager Nano, the available hazard information is used to assign specific nanoparticles to one of five hazard bands, labelled A to E (A= low hazard, E= highest hazard). Likewise, exposure bands are labelled 1-4 (1=low exposure, 4= highest exposure).

The hazard and exposure bands are combined to yield so called priority bands ranging from low priority (=4) to high priority (=1). A high priority implies that it is urgent to apply exposure control measures or to assess the risks more precisely, and a low priority implies that it is not very urgent to apply exposure control measures or to establish the risk involved with more precision.

See also Annex: *Human health and safety.*

Regulation and standards

International, European, national and regional data sources for regulation and standards include:

European documents:

- Regulation concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) - 1907/2006(EC);
- Regulation on Medical Devices - 2012/0266(COD); and
- European Commission Recommendation on the Definition of a Nanomaterial, as well as sectoral documents such as
- Nanomaterials in the Healthcare Sector: Occupational Risks & Prevention - E-fact 73; and
- Guidance on the Determination of Potential Health Effects of Nanomaterials Used in Medical Device.

National documents:

- Decree on the annual declaration on substances at nano-scale - 2012-232 (France);
- Royal Decree regarding the Placement on the Market of Substances manufactured at the Nano-scale (Belgium); and

[409] Van Duuren-Stuurman, B., Vink, S., Verbist, K.J.M., Heussen, H.G.A., Brouwer, D., Kroese, D.E.D., Van Niftrik, M.F.J., Tielemans, E., Fransman, W., 2012. Stoffenmanager Nano version 1.0: a web-based tool for risk prioritisation of airborne manufactured nano objects. Ann. Occup. Hyg. 56, 525-541.

- Order on a Register of Mixtures and Articles that contain Nanomaterials as well as the Requirement for Manufacturers and Importers to report to the Register – BEK nr 644 (Denmark).

H Concluding remarks

This Annex outlines the main methods for the selection of data for analysis, some data sources, the aggregation of data classes in order to enable analysis (mainly for the FP projects) and the ways in which data was analysed. References are made to some of the main quality control issues.

ANNEX 2: PHOTONICS KEYWORDS

Below is the list of keywords used in the extraction of data and the subsequent analyses.

Asterisks are used to indicate that part of a word is missing. For example, the search for "plasmon*" would identify data related to "plasmons" and "plasmonic". Thus, one search term was used to cover each of the words with multiple possible endings.

2-d photon polymerisation printing
Exciton*
Exciton-polariton
Glass photonic*
III-V photonic*
iii-v photonic*
III-V semiconductor photonic*
III-V/SI photonic*
III-V/silicon photonic*
Microstructure fibre*/ fibre*
Nanophotonic*
Nanostructure fibre*/ fibre*
Optoelectronic*
Opto-electronic*
Optogenetic*
Optronic*
PCF
Photo optical instrumentation
Photonic crystal fibre* / fibre*
Photonic crystal*
Photonic*
Photo-optical instrumentation
Plasmon*
Plasmonic metamaterial*
Polariton*
Silicon photonic*
Surface-plasmon polariton*
SPP*

ANNEX 3: ABBREVIATIONS

Abbreviation	Definition
BEUC	Bureau Européen des Unions de Consommateurs
CAGR	Compound Annual Growth Rate
CBRAM	Conductive Bridge Random Access Memory
CBRNE	Chemical, Biological, Radiological, Nuclear and Explosive
CEN	European Standardisation Committee
CMC	Chemistry, Manufacturing and Controls
CMOS	Complementary Metal-oxide Semiconductor
CNT	Carbon Nanotubes
COD	Co-decision Procedure
DFG	Deutsche Forschungsgemeinschaft
d-MRI	Diffusion Magnetic Resonance Imaging
DRAM	Dynamic Random-Access Memory
EC	European Commission
EEB	European Environmental Bureau
EFSA	European Food Safety Authority
EGE	European Group on Ethics Roundtables
EoL	End of Life
EPA	Environmental Protection Agency
EPR	Enhanced Permeation and Retention
ESD	Electrostatic Discharge
ETUC	European Trade Union Confederation
EU	European Union
Eurofound	European Foundation for the Improvement of Living and Working Conditions
FDSOI	Fully-depleted Silicon on Insulator
FET	Field Effect Transistor
f-MRI	Functional Magnetic Resonance
FP7	Seventh European Framework Programme
GMR	Giant Magnetoresistance
GOI	Germanium-on-insulator
ICT	Information and Communication Technologies
IPC	International Patent Classification
IPR	Intellectual Property Rights
ISO	International Organisation for Standardisation
JRC	Joint Research Centre
MAPP	Manual of Policies and Procedures
MEMS	Micro-electromechanical System
MNBS	Micro- and Nano-Bio Systems
MOSFET	Metal Oxide Semiconductor field-effect transistor
MR	Magnetic Resonance
MRAM	Magnetoresistive Random Access Memory
MRI	Magnetic resonance imaging
MRS (MRSI)	Magnetic Resonance Spectroscopy (imaging)
MWCNT	Multi-walled Carbon Nanotubes
MX2	Metal dichalcogenides
NACE	Nomenclature Statistique des Activités Economiques dans la Communauté Européenne

Abbreviation	Definition
NEMS	Nano-Electromechanical System
NGO	Non-Governmental Organisation
NIR	Near Infrared
NIR-II	Near-Infrared-ii Imaging
NOC	Network on Chip
NOMS	Nano-Optomechanical System
NP	Nanoparticles
NST	Nanoscience and Nanotechnology
NT	Nanotechnology
OFET*	Organic Field Effect Transistor
OLED	Organic Light-Emitting Diode
OSHA	European Agency for Safety and Health at Work
OSH-professional	Occupational Safety and Health Professional
PATSTAT	European Patent Office Worldwide Patent Statistical Database
PMC	Programmable Metallisation Cell
ppm	Parts Per Million
QD	Quantum Dot
R&D	Research and Development
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RRAM	Resistive RAM
SME	Small or Medium Sized Enterprise
SNAP	Strategic Nanotechnology Action Plan
SOI	Silicon-On-Insulator
SRAM	Static Random Access Memory
STOA	Science and Technology Options Assessment
STT MRAM	Spin Transfer Torque Magneto-Resistive Random Access Memory
STT RAM	Spin Transfer Torque Random Access Memory
SWCNT	Single Walled Carbon Nanotubes
TMDC	Transition Metal Dichalcogenide
TT	Technology Transfer
US	United States
US EPA	US Environmental Protection Agency
US NIOSH	US National Institute for Occupational Safety and Health
USA	United States of America
UV/Vis/IR	Ultraviolet / Visible / Infra-red
VC	Venture Capital
WEEE	Waste Electrical and Electronic Equipment

ANNEX 4: TERMINOLOGY

Word/phrase	Definition/explanation
Carbon nanotubes	Allotropes of carbon with a cylindrical nanostructure.
Dendrimers	Nanostructured synthetic molecules having evenly spread branching structure originating out of a central core.
Liposomes	An artificially-prepared vesicle composed of a lipid bilayer
Nanobiosensors	Biosensor at nano-scale: measurement system for detection of an analyte that combines a biological component with a physiochemical detector
Nano-biotechnology	Intersection of nanotechnology and biology, the ways that nanotechnology is used to create devices to study biological systems, this is different from bionanotechnology
Nanocapsule	Nano-scale shells made from non-toxic polymer
Nanocarrier	Nano-object or objects, which are at a larger scale but which carry nanoscale payloads able to transport a diagnostic or therapeutic agent either on its surface, within its bulk structure or within an internal cavity
Nano-coatings	Applying a coating of nano-scale structures to a surface.
Nanocrystal	Nano-object with a crystalline structure
Nanodiagnostics	Application of nanotechnology in molecular diagnostics
Nanoemulsion	Nanodispersion with a liquid matrix and at least one or more liquid nano-objects
Nano-enabled	Products, systems, devices integrating, using, enabled by nanotechnology
Nano-fibres	Nano-object with two external dimensions in the nanoscale and the third dimension significantly larger
Nano-indentation	Variety of indentation hardness tests applied to small volumes. For testing the mechanical properties of materials (hardness).
Nanomaterials	Materials the single units of which is sized (in at least one dimension) between 1 and 1000 nanometres (10^−9 meter) but is usually 1—100 nm (the usual definition of nano-scale).
Nanomedicine	Medical application of nanotechnology
Nanometres	One billionth of a metre
Nano-needles	Conical or tubular needles in the nanometre size range, made from silicon or boron-nitride with a central bore of sufficient size to allow the passage of large molecules
Nanoparticle	Small object that behaves as a whole unit with respect to its transport and properties, between 1 and 100 nanometres in size.
Nanopolymers	Nanostructured polymers
Nanoproducts	Any product containing nanoparticles
Nanorod	One morphology of nano-scale objects, produced by direct chemical synthesis.
Nano-scale	Refers to structures with a length scale applicable to nanotechnology, usually cited as 1–100 nanometres, also called nanoscopic scale
Nanoscience	The study of the fundamental and functional properties of matter on the nano-scale (~10^-9m).
Nanosensor (proteomic, gold)	Any biological, chemical, or surgical sensory points used to convey information about nanoparticles to the macroscopic world
Nanoshells (plasmon)	This is also called nanoshell plasmon, is a type of spherical nanoparticle consisting of a dielectric core, which is covered by a thin metallic shell (usually gold).
Nano-specific	Refers to a system or response that is sensitive to nanomaterials
Nanostructures	An object of intermediate size between microscopic and molecular structures

Word/phrase	Definition/explanation
Nano-suspensions	Submicron colloidal dispersions of nano-sized drug particles stabilised by surfactants. Nano-suspensions consist of the poorly water-soluble drug without any matrix material suspended in dispersion
Nanotechnologies / Nanotechnology	Manipulation of matter with at least one dimension sized from 1 to 100 nanometres
Nanotechnology-Based Platforms	Suit of technologies using nanomaterials, structures and objects
Nanotube	Hollow nano-fibre
Quantum Dots	A nanocrystal made of semiconductor materials that are small enough to exhibit quantum mechanical properties

ANNEX 5: ADDITONAL INFORMATION ON MEMBER STATE POLICIES AND PROGRAMMES

In addition to actions at the level of the whole of the European Union, many countries have developed strategies and action plans and funded programmes and projects. Some of these are identified and outlined below, by country.

The aim in this section is to give a flavour for the policies and programmes that are or have been in place for nanotechnology at Member State level, in the wider context of national strategies for science, technology, research and development. As it focusses on targeted initiatives for nanotechnology, not all EU28 countries are included.

This section has been prepared from existing data sources (e.g. Member State government and agency reports and web sites, European Commission sources (such as ERAWATCH/RIO[410]), evaluation reports). While efforts have been made to use the most up-to-date sources, it cannot be guaranteed that all information is current.

AUSTRIA

In Austria, the two main ministries involved in the funding of research and development (R&D) are the Federal Ministry of Science and Research (BMWF)[411] and the Federal Ministry for Transport, Innovation and Technology (BMVIT)[412]. The largest share of direct support for R&D is channelled through three funding agencies: The Austrian Science Fund (FWF)[413] that focuses on funding academic research; the Austrian Research Promotion Agency (FFG)[414] specialising in funding applied industrial research and the co-operation between the higher educational sector and industry; and the Austria Economic Service (AWS)[415] that is mainly active in support programmes for SMEs.

In 2004, the Federal Ministry for Transport, Innovation and Technology launched the "Austrian NANO Initiative" and in 2010, the "**Austrian Nanotechnology Action Plan**"[416] was adopted by the Federal Government. The NANO initiative was a response to regional activities in the Austrian Bundesländer (such as NanoNet Styria [for more information, see later in this Annex]) that sought to identify existing competences and to formulate potential themes for large-scale co-operative projects.

An important motivation in the establishment of such a national research programme was the expectation that its creation would strengthen the national research community in specific fields thereby better linking them to international communities. At that time, most Austrian peer countries (Germany, Switzerland, UK, and Finland), as well as the European Framework Programmes, were using the label nanotechnology for framing focused research programmes.

The NANO initiative aimed to address the following issues: What would be the best way for Austria to harness the opportunities in nanotechnology (for instance, in environmental and energy technology and new resource-saving products or for small- or medium-sized enterprises)? How could Austria contribute to ensuring the safety for its citizens of nanotechnology applications?

NANO had the following objectives: to increase networking among actors so as to achieve critical mass; to open up ways to exploit the benefits of nanotechnology for industry and society; and to ensure proper support for qualified personnel. To achieve these objectives, it had two programme action lines:

1. National co-operative RTD Projects (Research and Technology Development in Project Clusters (RPCs) and
2. Transnational co-operative RTD Projects (Research and Technology Development in Transnational Projects).

A key aspect of the **Nanotechnology Action Plan** to implement the NANO initiative was to strengthen communication and the dissemination of information to specific target groups, particularly the interested public. Information on the fundamentals, opportunities and risks of nanotechnology

[410] https://rio.jrc.ec.europa.eu/
[411] http://www.en.bmwfw.gv.at/
[412] https://www.bmvit.gv.at/en/
[413] https://www.fwf.ac.at/en/
[414] https://www.ffg.at/en
[415] http://www.awsg.at/
[416] https://www.bmlfuw.gv.at/dam/jcr:00058164-0320-4544-b6a4-320325dcfd86/Austrian%20Nanotechnology%20Action%20Plan.pdf

was provided to the public through an information portal for nanotechnology. A primary objective was to engage the public in the process of drawing up and implementing a Nanotechnology Action Plan[417], which underwent public consultation via the Internet in Autumn 2009, as did the Implementation Report in November 2012. The feedback received was published online and taken into account in the follow up to the Action Plan and Implementation Plan respectively.

One of the central measures of the Austrian Nanotechnology Action Plan was the establishment of a programme for the environment, health and safety (EHS). NANO EHS was established to provide targeted funding for environment- and health-related research into assessing the risks of synthetic nanomaterials.

NANO was implemented from 2004 to 2011 by the Austrian Research Promotion Agency (FFG)[418] and, in total, nine large-scale co-operative projects were funded across a wide array of sectors such as photonics, nanomedicine, and nanomaterials. Since 2012, support for nanotechnology R&D has been provided through the thematic programmes of FFG.

In addition to the above governmental actions, an Austrian network was created, **BioNanoNet**[419]**,** combining a wide range of expertise in numerous disciplines of medical and pharmaceutical research in nanomedicine and nanotoxicology. The BioNanoNet Association is also the owner of BioNanoNet Forschungs GmbH. Working across both biotechnology and nanotechnology, and visible at international levels, BioNanoNet addresses the scientific areas of:

- Nanotoxicology,
- Sensor technology
- Health and safety, including (nano-) medicine and nanosafety.

The BioNanoNet coordinates **EURO-NanoTOX[420]**, which is an open virtual centre and national platform. EURO-NanoTOX is co-funded by the Federal Ministry of Science and Research (BMWF). It elaborates strategies to conduct standardised toxicological in-vitro as well as in-vivo methods on nanostructured materials. Its main focus is on human nanotoxicology and human risk assessment.

Regional Nanotechnology initiatives:

Wirtschaftsstrategie Steiermark 2020 (2011)[421]: Styria's Economic Strategy 2020 is a successor to the State Government's previous economic strategy 2006. The 2006 strategy identified so-called economic and technological strong-points ("Stärkefelder") of the region, on which innovation policy activities were focused: material sciences; mechanical engineering/automotive and transport technologies; chemical and process engineering; human technology; information and communication technologies; environmental technologies; energy; building services engineering (including timber construction); nanotechnology; computer simulation and mathematical modelling. The 2011 strategy bundles activities in these fields under three major leading themes: i) mobility, ii) eco-technology, and iii) health technology. The central aim is to focus on future activities and to establish Styria as a "European benchmark for the structural change towards a knowledge based production-society".

BELGIUM

Since its two regions play a central role in Belgian policy making, the main nanotechnology activity in the country is carried by the regional government of Flanders, with a number of institutions working in the area of nanotechnology.

Strategische onderzoekscentra[422] (SOC's) is a strategy of the Region of Flanders which gives institutional funding to four Strategic Research Centres that collaborate with the academic and business worlds. Each of the institutes have their own specific focus.

- Imec[423] is a leading European independent research centre in micro- and nanoelectronics, *nanotechnology,* design methods and technologies for ICT systems. It carries out research that

[417] http://www.sozialministerium.at/cms/site/attachments/6/1/7/CH2120/CMS1371046721712/umsetzungsbericht_2012_en.pdf
[418] https://www.ffg.at/en
[419] http://www.bionanonet.at/about-bionanonet
[420] http://www.bionanonet.at/about-nanotoxicology?lang=english
[421] http://www.wirtschaft.steiermark.at/cms/beitrag/10430090/12858597
[422] http://www.ewi-vlaanderen.be/wat-doet-ewi/excellerend-onderzoek/strategische-onderzoekscentra
[423] http://www2.imec.be/be_en/home.html

runs three to ten years ahead of industrial needs. The world's top integrated device manufacturers, equipment and material suppliers, system houses and electronic design automation (EDA) vendors participate in the research conducted there. Work at Imec has a strong connection to nanotechnology given its use in electronics and as the next generation technology for electronics and ICT.

- VIB[424], the Flanders Institute for Biotechnology, is an autonomous entrepreneurial research institute that conducts strategic basic research in life sciences, including molecular biology, cell biology, developmental biology, structural biology, genetics, biochemistry, microbiology, genomics and proteomics. It is considered to be a leading European centre. Much of its work is at the *nanoscale*.
- VITO[425], the Flemish Institute for Technological Research, is an independent contract research and consulting centre. It converts the latest scientific knowledge and innovative technologies into practical applications, both for public authorities and industry. The research centre operates in the fields of energy, environmental and material technology, in industrial product and process technologies and in remote sensing, with *nanotechnology* applications.
- iMinds[426] is an independent research institute that stimulates innovation in information & communication technology (ICT) and broadband. This research is interdisciplinary and demand-driven, and takes place in close collaboration with businesses and governments, both local and international. Its aim is to provide solutions to complex problems and thus help meet society's future challenges.

In 2003, the Regional Government of Wallonia launched a nanotechnology program in order to support research projects in that field which led to the creation of **NanoWal[427]**, a structure to favour interactions between actors in nanotechnology field. Nanowal became a non-profit organisation in 2009.

THE CZECH REPUBLIC

In 2005, the Academy of Sciences of the Czech Republic approved the programme "**Nanotechnology for the Society**" with the objective of achieving progress in the development of research and utilisation of nanotechnologies and nanomaterials within Czech society[428]. It included four different sub-programmes in the areas of: nanoparticles, nanofibres and nanocomposite materials; nano-biology and nanomedicine; nano-macro interface; and new phenomena and materials for nano-electronics, with specific priorities in all of them. The programme was planned to end in 2012.

Other general programmes with a less specific mention to nanotechnology came from the Grant Agency of the Czech Republic, the Ministry of Education, Youth and Sports and the Ministry of Industry and Trade.

In the National Research, Development and Innovation Policy document of the Czech Republic in 2009-2015[429], nanotechnology is addressed under the **Materials Research** priority, where it is set as an area to be supported by national budget in order to increase the global competitiveness of the Czech economy through products with high added-value.

DENMARK

In Denmark, the Ministry of Higher Education and Science[430] has the main responsibility for research and innovation policy.

In the period from 2001 to 2004, steering groups set up by the Danish government carried out a Technology Foresight pilot programme. The aim of the programme was to carry out eight foresight studies in the three-year period, and to identify issues of strategic importance for science, technology, education, regulation and innovation policy in these areas. The foresight studies included bio- and health care technologies, and ICT (pervasive computing, future green technologies, hygiene and nanotechnology, especially nanomedicine[431]). The last phase of the foresight programme was

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[424] http://www.vib.be/en/Pages/default.aspx
[425] https://vito.be/en
[426] https://www.iminds.be/en
[427] www.nano.be/
[428] http://www.csnmt.cz/getfile.php?type=file&IDfile=24
[429] http://www.vyzkum.cz/FrontClanek.aspx?idsekce=1020
[430] http://ufm.dk/en
[431] Danish Nano-science and Nano-technology for 2025, Foresight Brief No. 032

closely linked to the establishment of the Danish National Advanced Technology Foundation[432] for the development of generic technologies of future importance such as ICT, biotechnology and nanotechnology.

The Action Plan "Strategy for Public-Private Partnership on Innovation", launched in 2003, focused on how to improve co-operation between education, research and trade/ business. The goal was for more enterprises, especially SMEs, to have faster and easier access to knowledge. In 2004, the Ministry of Science, Technology and innovation issued **the Technology Foresight on Danish Nanoscience and Nanotechnology – Action Plan**[433] as a basis for Danish policy on research, education and innovation in the area. The vision was to raise awareness of and promote the utilisation of nanotechnology in Denmark.

In 2003, on foot of the above developments, the Ministry of Science, Technology and innovation published a call for the establishment of high-tech public-private networks in bio, nano and information technology. The goal was to create stable collaboration patterns between companies and knowledge institutions to increase knowledge transfer to, and use in, private industry. The funding was to be used to finance networking. In the first round (in 2004) the Ministry provided seven networks with a budget of EUR 3.7 million (around EUR 0.5 million each). Amongst the networks was NaNet which, (together with Nano Øresund) became one of the two most important Danish nanotechnology networks. NaNet's mission was to create platforms for the exchange of information on nanotechnology, and to facilitate its utilisation on all levels of society, from research and education to industrial application and development.

Between 2005 and 2010, EUR 116 million was allocated to strategic research centres, research alliances and research projects, EUR 62 million being for nanotechnology, biotechnology and ICT. Among the strategic research centres funded under the programme is a Centre for Nano-vaccines[434].

Since 2009, the Danish National Advanced Technology Foundation has channelled funding for projects in high-tech sectors, such as nanotechnology, biotechnology and ICT.

Support for nanotechnology research has been managed through a number of sources. The Danish Council for Strategic Research, part of the Danish Agency for Science, Technology and Innovation is one of these, although the council itself did not authorise funds for research, dependent instead on the Programme Commission, which covers Nanoscience, Biotechnology and IT (NABIIT). The Strategic Research Programme for the Interdisciplinary Applications of NABIIT technologies supported the establishment of networks and research initiatives. Research support also came from the Danish National Research Foundation, the Danish Ministry of the Interior and Health's inter-ministerial working group on Nanotechnology and Human Health, and the Danish National Advanced Technology Foundation. Latterly, also under the Danish Council for Strategic Research, the Programme Commission on Strategic Growth Technologies has had annual calls of total annual value approximately EUR 10 million for research projects on nanotechnology, biotechnology and information- and communication technology. In 2013, The Danish government and five political parties decided to revise the research and innovation system, agreeing to merge the Danish National Advanced Technology Foundation, the Danish Council for Strategic Research and the Danish Council for Technology and Innovation into a new innovation foundation. Thus, the new organisation Innovation Fund Denmark[435] (IFD), has been the responsible body since 2014.

FINLAND

The main focus areas of public research and development (R&D) funding in Finland are energy and the environment, health and well-being, the information and communications industry, the forest cluster, and metal products and mechanical engineering. Nanotechnology is treated as a technology to be applied across all these focus areas. Finland spends approximately 3.5 % of its gross national product on (R&D). Exploitation of research results being seen as even more important than the amount of investment, the Finnish innovation environment seeks to promote the exploitation of scientific and technological results in Finnish companies.

The main research policy decisions are drawn up in the Science and Technology Policy Council of

[432] http://www.tekno.dk/about-dbt-foundation/?lang=en
[433] http://ufm.dk/en/publications/2004/technology-foresight-on-danish-nanoscience-and-nanotechnology
[434] http://www.nano-vaccine.org/
[435] http://innovationsfonden.dk/en; In 2015, IFD had an annual budget of DKK 1.6 billion, but their budget is expected to decrease to DKK 1.47 billion in 2016. The total budget for innovation funds areas was over DKK 2 billion in 2010, so a significant loss of funding took place during the last 5 years.
http://innovationsfonden.dk/da/nyhed/innovationsfonden-investerer-ogsaa-i-forskernes-gode-ideer

Finland chaired by the Prime Minister. The principle instruments in the implementation of the policy are the funding organisations working under the ministries. Tekes, the Finnish Funding Agency for Technology and Innovation operates under the remit of the Ministry of Trade and Industry while the Academy of Finland is governed by the Ministry of Education. Nearly 80% of all public research funding is channelled through these two organisations.

The **first Finnish nanotechnology programme** was financed jointly by Tekes and the Academy of Finland in 1997–1999[436]. Its objective was to build know-how, multi-disciplinary infrastructure and linkages between fundamental and applied research. The programme also established a new form of co-operation using joint funding between Tekes and the Academy of Finland. The total value of the programme was EUR 7 million (Tekes EUR 4m, the Academy of Finland EUR 3 m).

FinNano, the Finnish nanoscience and nanotechnology programme, was established in 2005. The programme was co-ordinated jointly by Tekes and the Academy of Finland and covered the whole innovation chain from basic research to commercial products. The aim of the programme was to strengthen Finnish nanotechnology research in selected focus areas and to accelerate the commercial development of nanotechnology in Finland. The key objective was to boost internationally recognised high-level research and competitive business based on nanotechnology.

In addition to FinNano, the Ministry of Education provided funding to develop nanoscience education and infrastructure in Finnish universities and the Nanotechnology Cluster Programme was initiated in 2007 with the Centre of Expertise Programme. In total, Finnish public funding for nanotechnology during 2005–2010 was approximately EUR 235m.

In practice, the FinNano programme was executed in two parts: Tekes' FinNano – Nanotechnology Programme (2005–2009) and the Academy of Finland's FinNano – Nanoscience Programme (2006–2010). The Programme had a total value of approximately EUR 70m, including EUR 25m in research funding and EUR 20m in corporate financing from Tekes. The original programme plan defined three main focus areas:

1) Innovative nanostructure materials;
2) Nano-sensors and nano-actuators; and
3) New nano-electronics solutions.

In 2007, the aims of the programme were redefined as being for:

- Society: Renewal of industry clusters and production, environment and safety;
- Applications: Electronics, forest cluster, chemical sector, health and well-being; and
- Technologies: Nanostructured and functional materials, coatings and devices; Measurement methods, production and scalability.

According to a programme's interim evaluation in 2008, the main successes of FinNano were to activate companies in research and product development, to map all the existing nanotechnology infrastructure and to create cross-cutting networks of nanotechnology professionals.

In 2011, the final report on FinNano was published, showing the results of the Programme[437]. According to that report and an independent evaluation by Gaia Consulting Ltd., all the Finnish nanotechnology programmes succeeded and fulfilled their objectives, which ranged from capturing knowledge in nanoscience and technology to boosting Finnish nano research and business. The next steps in the development of nanotechnology for industry in Finland were recommended to be achieved by other means. These included measures to enhance technology transfer, encouragement of entrepreneurship, and seed funding and basic research funding based on problems and not in disciplines.

In more recent years, Finland has therefore stopped identifying nanotechnology as a separate area for funding, opting to fund it under general R&D funding programmes and actions to enhance technology transfer and commercialisation by industry in Finland.

France

In 1999, the "**French Research Network in Micro and Nano Technologies**" (RMNT) was created for the purpose of strengthening and reorganising micro- and nano research and aligning it with the private sector.

In 2003, a **network of major technology centres** was created, linking together the facilities at

[436] http://www.tekes.fi/globalassets/julkaisut/research_and_technology.pdf
[437] http://www.tekes.fi/globalassets/julkaisut/finnano_loppuraportti.pdf

the following organisations:

- *CEA-LETI*[438] in Grenoble (centred in Minatec);
- The *Laboratoire d'Analyses et d'Architectures des Systemes*[439] (LAAS) in Toulouse ;
- The *Laboratoire de Photonique et de Nanostructures*[440] (LPN) in Marcoussis ;
- *The Institut d'Électronique Fondamentale*[441] *(IEF) Orsay,* in Minerve; and
- The *L'Institut d'Electronique, de Microélectronique et de Nanotechnologie* [442] (IEMN) in Lille.

The creation of this network was supported by a total subsidy of EUR 100 million for the period 2003 to 2006.

Launched in 2003 to fund fundamental research, France's national **Nanosciences Programme** was co-ordinated by the Ministry of Research in co-operation with the CNRS (National Scientific Research Centre), the CEA (French Atomic Energy Commission) and the DGA (General Delegation for Weaponry).

In 2005, the French National Research Agency (ANR) was established to assume responsibility for the funding and organisation of all national R&D projects, in order to improve co-ordination. Today, national nano research is funded within the national programme for nanosciences and nanotechnologies (**PNANO**[443]) under the ANR. The budget of the ANR for 2005 was EUR 539m, EUR 35.3m of which was dedicated to PNANO. The ANR has funded research projects in nanosciences and nanotechnologies mostly through the following research programmes:

- Non-thematic programmes (called "programmes blancs")
- Nanotechnologies and Nanosystems programmes P2N.
- Additional programmes, which are more specific to a given topic, such as those on hydrogen storage and fuel cells or on home photovoltaics.

A EUR 35 billion economic stimulus package **Investissements d'Avenir**[444] (Investments for the Future) was launched at the end of 2009. Within that context and since 2011, nano-bio-technology has been one of the priority areas for funding under the ANR, with a particular focus on health and environmental research. The package aims to support scientific research, accelerate its transfer to a pilot stage and to consolidate knowledge about toxicology and nanomaterials, the programme is funding therapies, imaging, diagnostics and medical devices base on nanotechnology and biotechnology.

GERMANY

As far back as 1998, the Federal Ministry of Education and Research (BMBF) increased collaborative project funding for nanotechnology. In addition, an infrastructure plan was put in place in the form of the establishment of six competence centre networks. The measures were implemented two years before the USA began its national nanotechnology initiative and four years before the European Union's comparable measures under the Sixth Framework Programme.

In 2004, the German Innovation Initiative for Nanotechnology - "**Nanotechnology Conquers Markets"**[445] was launched and presented to the public. On the basis of the White Paper presented at the nanoDe congress in 2002 and intensive discussions with representatives from business and science, the BMBF's new approach to nanotechnology funding was based on Germany's highly-developed and globally competitive basic research in sciences and technology and primarily aimed to open up the application potential of nanotechnology through research collaborations (leading-edge innovations) that strategically target the value-added chain. The main elements of the strategy were to open up potential markets and boost employment prospects in the field of nanotechnology. Five leading-edge innovation programmes were funded initially:

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[438] http://www-leti.cea.fr/en/
[439] https://www.laas.fr/public/
[440] http://www.lpn.cnrs.fr/fr/Commun/
[441] http://www.ief.u-psud.fr/
[442] http://exploit.iemn.univ-lille1.fr/
[443] http://www.agence-nationale-recherche.fr/suivi-bilan/historique-des-appels-a-projets/appel-detail1/programme-national-en-nanosciences-et-nanotechnologies-pnano-2005/
[444] http://www.gouvernement.fr/investissements-d-avenir-cgi
[445] http://d-nb.info/97392179x/34

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- NanoMobil, for the automotive sector;
- NanoLux, for the optics industry;
- NanoforLife, for pharmaceuticals and medical technology;
- NanoFab, for electronics; and
- NanoChance, a BMBF funding measure for targeted support of R&D -intensive small and medium-sized enterprises.

Existing policy actions were re-organised under the umbrella of the **High-Tech Strategy**[447] in 2006. This was done through the **Nano Initiative—Action Plan 2010**[448], a cross-departmental initiative by seven departments of the Federal Government that started in 2007 and was headed by the BMBF. Tying in with BMBF's 2004 Innovation Initiative for Nanotechnology, the action plan aimed to integrate nanotechnology funding in the various policy fields into a national nanotechnology strategy. The Action Plan's main goals were (1) to speed up the use of the results of nanotechnological research for innovations; (2) to introduce nanotechnology to more sectors and companies; (3) to eliminate obstacles to innovation by means of early consultation in all policy areas; and (4) to enable an intensive dialogue with the public. The focus was on the opportunities offered by nanotechnology, but possible risks were also taken into account. The total funding for the years 2007 to 2009 was EUR 640 million.

In 2011, the German Ministry for Education and Research (BMBF) published the **Action Plan Nanotechnology 2015**[449], outlining the strategy for responsible development, innovation and public dialogue for the period 2010-2015. The plan included proposals for developing nanotechnology in five main areas (climate/energy, health/food and agriculture, mobility, communication and security). In parallel, a new funding instrument was launched - **Innovation Alliances** - to provide funding for strategic co-operation between industry and public research in key technology areas that demand a large amount of resources and a long time horizon, but promise considerable innovation and economic impacts. Public funds and funding from the industry is combined in a typical proportion of 1:5 (public: private). Innovation was supported with special emphasis on SMEs and development of value chains. Risk assessment was incorporated as well as an improvement of boundary conditions such as educating the workforce, and addressing issues of legislation, norms and standards. The public dialogue on nanotechnology was intensified, including information and dialogue with citizens as well as stakeholders and NGOs.

Innovation alliances were launched as a successor to the leading-edge innovation programmes. They were planned as an instrument of public support to ground-breaking industrial innovation, providing support funding for strategic co-operation between industry and public research in high-potential technology areas that require high levels of funding and long lead times. Through a public-private partnership, the Federal Government provided funding for R&D and other innovation-related activities for specific, long-term co-operative R&D projects. R&D activities could range from fundamental research to prototype development. Public funds were complemented by private money from industry, typically at a proportion of 1:5 (public: private). Each innovation alliance was set up through an industry initiative, organised as a long-term co-operative research project and involving

[446] http://d-nb.info/97392179x/34
[447] http://www.research-in-germany.org/en/research-landscape/r-and-d-policy-framework/high-tech-strategy.html
[448] http://www.cleaner-production.de/fileadmin/assets/pdfs/Nano_initiative_action_plan_2010.pdf
[449] http://www.lai.fu-berlin.de/homepages/nitsch/publikationen/Germany_ActionPlanNanotechnology_2015.pdf

several industry partners as well as public research organisations.

An Innovation Alliance that followed this policy approach was on "Molecular Imaging for Medical Engineering" (nanotechnology) and was formed by Bayer Schering Pharma AG, Boehringer Ingelheim Pharma GmbH & Co. KG, Carl Zeiss AG, Karl Storz & GmbH Co. KG and Siemens AG. The alliance's goal was creating new diagnostic agents and imaging procedures for clinics and the development of pharmaceuticals.

In addition to policies and programmes to support R&D and commercialisation, Germany took action to address concerns about the environmental and safety costs of the nanotechnology. These are particularly important to look at when trying to develop and label commercial nanotechnology products for the market. In response to these issues, governments have increasingly included the concept of responsible development in their nanotechnology activities. Responsible development aims to stimulate the growth of nanotechnology applications in diverse sectors of the economy, while addressing the potential risks and the ethical and societal challenges the technology might raise. Germany has dedicated policies for the responsible development of nanotechnology. The report "Responsible Handling of Nanotechnologies" ("Verantwortlicher Umgang mit Nanotechnologien") launched by the Nano-Commission of the German Federal Government in December 2010 showed that the nanotechnology sector is continuing to develop dynamically.

Regional initiatives in Germany that make specific mention of nanotechnology include:

- Innovation Strategy of Nordrhein-Westfalen (2006): This strategy was a government statement dated 26 June 2006. It presented a short analysis of the importance of innovations for North Rhine-Westphalia, and in the following elaborated the overall strategy and the measures employed and purposes targeted. The government strategy aimed to generate new potential for growth by reinforcing strengths, sharpening profiles, promoting excellence and pooling forces. Thus, the funding of research and technology was focused on four priority areas with high potential both related to innovation, employment and growth: (i) *nanotechnology,* microtechnology and new materials; (ii) biotechnology; (iii) energy- and environmental research; and (iv) medical research, medical engineering.
- Cluster Offensive Bayern (2007)[450]: The Bavarian cluster policy was initialised in 2007 and focused on 19 branches/technologies with high importance for the future of Bavaria. These were organised into five fields:
  - materials engineering (including *nanotechnologies*, materials engineering, chemical industries);
  - mobility (including automotive, rail, logistics, aerospace and satellite navigation);
  - life sciences and environment (including biotechnology, medical technologies, energy technologies, environmental technologies, forestry and food);
  - IT and electronics (ICT, high-performance electronics, mechatronics and automation); and
  - service and media (financial services, media).

After a positive evaluation in 2010, the State Government announced some changes in the future organisation of the overall initiative: A major change is that the (nonetheless successful) clusters high-performance electronics, logistics, biotechnology and medical technologies would be restructured into networks, while future funding would be focused on the other clusters, where funding so far was most successful in generating additionality.

- Research Strategy of Thuringia (2008): Main objectives of Thuringia's research policy were to strengthen regional universities and non-university research institutes and regional companies in their research and development efforts in order to achieve scientific excellence, to initiate knowledge and technology transfer as well as innovation. The document described outstanding research areas of the state and measures to strengthen and relate the regional research landscape to target fields in the regional economy: cultural and social change; media and communication; health research and medical technology; microbiology and biotechnology; optical technologies, photonics; micro and nano technologies, microelectronics; information and communication technologies; materials and production technologies; environmental and energy technologies, infrastructure. Main fields of activity of regional research policy were (i) to support competitiveness, (ii) to strengthen networks, (iii) to support young researchers, and (iv) to invest in infrastructure.

[450] https://www.cluster-bayern.de/en/

IRELAND

Following the establishment of Science Foundation Ireland (SFI) in 2000, public funding was made available to support many public research initiatives including the **Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN)[451]**. Since its foundation in 2003, CRANN has become a research institute of international standing with 17 Principal Investigators (PIs) across multiple disciplines including physics, chemistry, medicine, engineering and pharmacology, and a total of 250 researchers. CRANN was funded predominately by Science Foundation Ireland (SFI), in partnership with two universities (Trinity College Dublin and University College Cork) and industry, and was formed to harness the cross-disciplinary nanoscience research of individual PIs to deliver world leading research outputs and to enable CRANN researchers to address key industry challenges.

In addition, in December 2009, the **Competence Centre in Applied Nanotechnology (CCAN)** was launched. It was an industry-led, collaborative, applied research centre enabling its member companies and research providers to work together to develop nanotechnology enabled products and solutions for the ICT and biomedical industries (i.e. diagnostics, drug delivery, and regenerative medicine). It was co-hosted by CRANN and Tyndall National Institute at University College Cork. With a growing membership, the founding industry members were Aerogen, Analog Devices, Audit Diagnostics, Creganna-Tactx, Intel, Medtronic, Proxy Biomedical and Seagate. CCAN ran until mid-2015.

Ireland has developed its reputation in nanoscience with its researchers recently ranked sixth globally for the quality of their research. Active collaborations between industry and academia exists and are beginning to deliver significant economic benefits to Ireland. Three of the largest industries in Ireland are directly impacted by nanoscience research in perhaps – medical devices, pharmaceuticals and ICT.

The industry ministry, the Department for Jobs, Enterprise and Innovation (formerly the Department of Enterprise, Trade and Employment) plays a pivotal role in industrial innovation policy with its agencies, Enterprise Ireland (EI) (responsible for supporting Irish companies); Science Foundation Ireland (SFI) (funding basic and applied research); and IDA Ireland (in charge of overseas inward investments).

Apart from the establishment of research infrastructures, policy priorities were also being addressed in the Irish national innovation system. In 2004, the Irish Council for Science, Technology and Innovation, with its Secretariat provided by Forfás, launched **its ICSTI Statement on Nanotechnology**. The Statement assessed Ireland's capabilities in the field of nanotechnology, mapped out specific areas of opportunity for the Irish economy and presented a sustainable vision and strategy for the promotion, development and commercialisation of nanotechnology in Ireland. Among the key application areas that were identified were also pharmaceutical and medical technologies.

In 2010, Forfás[452] itself launched a report on **'Ireland's Nanotechnology Commercialisation Framework 2010 – 2014'**. The report presented a national framework to position Ireland as a knowledge and innovation centre for certain niche areas of nanotechnology. It highlighted that Ireland's nanotechnology players should focus on three main technology areas (advanced materials, "More than Moore" and nanobiotechnology) and four application areas (next generation electronics, medical devices & diagnostics, environmental applications, and industrial process improvements).

The BioNano Laboratory in CRANN (mentioned above) is dedicated to interdisciplinary research at the interface between the physical and life sciences including nanotechnology and diagnostics, nanotoxicology and nanomedicine. The group investigates molecular, cellular and physiological interactions using novel biophysical tools such as cell actuators, and magnetic and ultrasound fields. Members of the BioNano Laboratory are also members of the **Integrated Nanoscience Platform for Ireland (INSPIRE)[453],** a consortium of all Irish third level institutions with international leading research capability in nanoscience and nanotechnology. Furthermore, CRANN is also part of the Molecular Medicine Institute which is a not for profit company established by an extended network of Irish Universities and their associated academic hospitals. The BioNano Laboratory aims to facilitate and accelerate the translation of biomedical nanotechnology research into improved nanoscale diagnostics and nanomedicine.

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[451] http://www.crann.tcd.ie/

[452] Forfás ceased to exist in 2015 and was, in part, subsumed under the Department of Jobs, Enterprise and Innovation.

[453] http://www.crann.tcd.ie/Research/Academic-Partners/testt.aspx

In October 2013, a new Science Foundation Ireland funded research centre, **Advanced Materials and BioEngineering Research (AMBER)**[454] was launched. AMBER is jointly hosted in TCD by CRANN and the Trinity Centre for BioEngineering, and works in collaboration with the Royal College of Surgeons in Ireland and UCC. The centre provides a partnership between leading researchers in material science and industry to develop new materials and devices for a range of sectors, particularly the ICT, medical devices and industrial technology sectors.

THE NETHERLANDS

In the Netherlands, nanotechnology was established as a distinct field of scientific research in the early years of the 21st century. A foresight study (Ten Wolde 1998) conducted by the Dutch Study Centre for Technology Trends (STT) between 1996 and 1998 laid the foundation of a national research agenda. The study showed the importance of nanotechnology for electronics, materials, molecular engineering and instrumentation, and also recommended to pay due attention to nanosafety issues and set up research in that area.

The Netherlands hosts three dedicated nanotechnology research centres: The University of Twente (with the **Mesa+** research centre in microsystems technology and nanomaterials[455]), Delft University of Technology (with the **Else Kooi Laboratory**[456], previously called Dimes research centre on nanoelectronics) and the University of Groningen (with **BioMaDe**[457] focused on bio-nanotechnology). The early 2000s, these formed the core of **NanoNed** - the Nanotechnology R&D initiative in the Netherlands[458]. NanoNed was initiated after three years of preparatory work in 2004 by nine industrial and scientific partners including Philips and TNO. It clustered the Dutch expertise on nanotechnology and enabling technology into a national network. The total budget of the NanoNed programme amounted to EUR 235 million, funded by the Dutch Ministry for Economic Affairs. The NanoNed programme was organised into eleven independent programmes or flagships. Each of those was based on regional R&D strength and industrial relevance. The flagships were Advanced NanoProbing, BioNanoSystems, Bottom-up Nano-Electronics, Chemistry and Physics of Individual Molecules, Nano Electronic Materials, NanoFabrication, Nanofluidics, NanoInstrumentation, NanoPhotonics, Nano-Spintronics and Quantum Computing.

In 2006, the Cabinet vision on Nanotechnology "**From Small to Great**" was published. The content of the document mirrored the outline of the European Commission's 2005 Action Plan, with sections on business and research opportunities; societal, ethical, and legal issues; public engagement; and risk assessment.

In 2008, the Dutch Government published its **Nanotechnology Action Plan**[459]. The plan, prepared by the Interdepartmental Working Grou #p on Nanotechnology (ION) and building on the 2006 vision document, incorporated the most up-to-date scientific findings, and reflected information and agreements from European Union and other international initiatives. Four generic themes were defined on the basis of the central theme impact on society and risk analysis, i.e.: bio-nano-technology, beyond Moore, nanomaterials, and nano production (including instrumentation and characterisation). In addition, four application areas were singled out: clean water, energy, food and "nanomedicine".

The Dutch systematic approach to nanotechnology strategy resulted in the development of stable research groups, centres, department and laboratories. On the national level, **NanoLab NL**[460] formed a consortium that built, maintained and provided a coherent and accessible infrastructure for nanotechnology research. NanoLab drew on government funding, which was first spent on upgrading existing infrastructure. Only when the existing infrastructure was fully used and a well-characterised additional need was identified and additional investment made. As a consequence, the Dutch nanotechnology research infrastructure was heavily used by research groups and the local industry. The partners in this enterprise considered themselves often as competitors but co-operate and co-ordinate their actions because of the substantial government funding.

In 2011, the **NanoNextNL**[461] national research programme on nanotechnology was started as a

[454] http://ambercentre.ie/
[455] https://www.utwente.nl/mesaplus/
[456] http://ekl.tudelft.nl/EKL/Home.php
[457] http://www.biomade.nl/
[458] However, four other universities, and TNO, the Netherlands Organisation for Applied Scientific Research, are also represented.
[459] http://www.rritrends.res-agora.eu/uploads/27/8079721-bijlage%281%29.pdf
[460] http://www.nanolabnl.nl/
[461] http://www.nanonextnl.nl/

continuation of NanoNed and MicroNed (the Netherlands Microtechnology program). NanoNextNL is based on a Strategic Research Agenda that was asked for by the government in both the cabinet and the action plan. Risk evaluation and Technology Assessment form part of this research programme. 15% of the budget is dedicated to risk-related research, as was demanded by government in the action plan. It is planned that NanoNextNL programme will finish in 2016 but anticipated that many aspects of it will be continued under an industry umbrella. Since 2011, the research agenda for nanotechnology is also part of the **Top sector policy of the Netherlands**[462], which aims to enhance the knowledge economy by stimulating nine top sectors (leading economic sectors).

The Top sector policy is implemented via innovation contracts, in which agreements are laid down between business leaders, researchers and government, jointly focusing the available resources for knowledge and innovation towards the leading economic sectors. Support programmes that aim to support the development and deployment of nanotechnology, are mostly project based. The formats for such supports range from small business oriented measures to financing large research project which involve co-operation between private and public research performers.

POLAND

In 2000, the Polish State Committee for Scientific Research (KBN) started a targeted research project in the topic of nanotechnology called "**Metallic, Ceramic and Organic Nanomaterials: Processing – Structure – Properties – Applications**" with two aims:

- stimulating research on nanomaterials in Poland and promoting collaboration between researchers in this field; and
- making a landscape of the status of nanotechnology in Poland.

The project involved 15 scientific institutions working on 26 research tasks.

In the Polish National Development Plan for the years 2007-2013, launched by the State Committee for Scientific Research in Warsaw in 2004, nanotechnology was foreseen as an area that should contribute to achieving a significant competitive potential in the European Arena.

During 2006, the Ministry of Science of Higher Education established the Interdisciplinary Committee for Nanoscience and Nanotechnology. This Committee analysed the nanotechnology situation and capabilities in Poland and proposed the basic fields that should be strategically supported and launched in 2007 the "**Strategy for the Reinforcement of Polish Research and Development Area in the Field of Nanosciences and Nanotechnologies**"[463]. The areas to be supported were nanoscale phenomena and processes, nanostructures, nanomaterials and nanoscale devices on the one side and nano-analytics/nano-metrology and manufacturing processes and devices for nanotechnology on the other. The priority of the strategy of nanosciences and nanotechnologies was the development, co-ordination and management of the national system of research, education and industry in this field in the short-, medium-, and long-term perspective. Other main objectives to be achieved by 2013 were the development of high added-value nanotechnology products, the creation and commercialisation of manufacturing devices for the production of nanomaterials, the development of the education system in the field of nanotechnology, educating about 20-30 doctors yearly in the specialisation of nanotechnology, building specialist laboratories, establishing co-operation networks of research and industrial units, financial institutions, etc. and integrating dispersed activity of research units in a joint programme of nanotechnology development.

In 2014, the Government approved the **National Smart Specialisation Strategy** as an integral part of the Enterprise development Programme, setting "Multifunctional materials and composites with advanced properties, including nano-processes and nano-products" as a horizontal smart specialisation area in Poland.

PORTUGAL

In 2005, the Portuguese and Spanish Governments decided to jointly create the **International Nanotechnology Laboratory (INL)[464]** in Braga, Portugal, which was partly funded under the European Regional Development Fund (ERDF). The decision of Portugal and Spain to create an international research laboratory was announced by the head of Government of Spain and the Prime Minister of Portugal at the end of the XXI Portugal-Spain Summit that took place in Évora, Portugal.

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462 http://topsectoren.nl/english
463 www.bioin.or.kr/fileDown.do?seq=5186
464 http://inl.int/

The International Nanotechnology Laboratory (INL) was installed in Braga, Portugal, its Director is the Swedish Professor Lars Montelius, and it has over 90 employees.

INL concentrates on nanotechnology, and considers applications to several other areas, following a truly interdisciplinary approach. The Laboratory has been conceived to:

- Assure world class research excellence in all areas of activity;
- Develop partnerships with the industry and foster the transfer of knowledge in economic values and jobs;
- Train researchers and contribute to the development of a skilled workforce for the nanotechnology industry; and
- Survey, prevent and mitigate nanotechnology risks.

Among its research areas nanomedicine, nano-electronics, nano-machines & nano-manipulation and environment monitoring, security and food quality control can be found.

Further information on the policies and programmes of Spain is given below.

SPAIN

The Minister of Economy and Competitiveness is responsible for the design of the national innovation strategy in Spain. An Inter-Ministerial Commission on Science and Technology (CICYT) has the role of co-ordinating the actions of the different bodies involved in innovation policy in a complex governance structure. The regions of Catalonia, the Basque Country and Valencia are especially active in S&T policy.

The 2004-2007 R&D plan was the first Spanish national R&D plan containing a specific cross-programme action regarding nanoscience and nanotechnology. The **Strategic Action (SANSNT)** was designed for the overall enhancement of Spanish industry competitiveness through the implementation of deep changes in several industrial sectors by generating new knowledge and applications based on the convergence of new technologies, where nanotechnology plays a central role. The SANSNT included seven thematic lines among which the first one is "***Nanotechnologies*** applied in materials and new materials within the field of health". Also included are systems biology, synthetic biology and *nanobiotechnology*. The Strategic Action encompassed the development of activities within the six Instrumental Lines of Action (human resources; projects; institutional strengthening; infrastructures; knowledge use; and articulation and internationalisation of the system).

Nanoscience and nanotechnology were included as a **Strategic Action** of both the 2004-2007 National Plan for Research, Development and Innovation (R+D+I) and the funding set aside within this Plan for the Industrial Sector (PROFIT Programme), with the aim of promoting the development of industrial projects (carried out by companies) with nanotechnology-focused objectives.

During the 2004-2007 periods, around 40 projects were funded as a result of this Strategic Action, receiving a total of EUR 2 million in subsidies and EUR 8.5 million in associated investments. All the projects were coordinated by industrial companies, although universities and technological centres were involved in the development of many of them either on a collaborative basis, or were subcontracted by the company carrying out the project.

In 2005, the Government of Spain launched the strategic programme **INGENIO 2010**[465] to align Spain with the strategy of the European Union to reach a 3% of the GDP invested in R&D by year 2010, thereby reducing the gap between Spain and other countries. Its general objective was to achieve a gradual focus of Spanish resources on strategic actions to meet the challenges faced by the Spanish Science and Technology System. This was to be achieved by continuing the existing policies, agendas and successful programmes, as well as by implementing new actions needed to finish meeting the challenges identified for the national science, technology and engineering system.

In order to enhance critical mass and research excellence, the goals of the INGENIO 2010 Programme, within the **CONSOLIDER programme** (launched by the Ministry of Education and Science, through the General Secretariat of Scientific Policy, to promote high quality research and to reach critical mass and research excellence), included creating Centros de Investigación Biomédica en Red (Biomedical Research Networking Centres, CIBER) by setting up consortia, with their own legal personality, without physical proximity, which were designed to conduct single-topic research on a specific broadly-defined disease or health problem. CIBER were formed through the association of research groups linked to the national health system to help form the scientific basis of the

[465] http://www.ingenio2010.es/

programmes and policies of the national health system in the priorities areas of the National R+D+I Plan. Among the centres that have been created within this programme is the Biomedical Research Networking centre in Bioengineering, Biomaterials and ***Nanomedicine*** (CIBER-BBN), founded in 2006. The ***Nanobiomed consortium***, which researches the use of nanoparticles for drug delivery, was also founded with CONSOLIDER funds.

Between 2008 and 2011 the **National Strategy of Nanoscience and nanotechnology, new materials and new industrial products**[466] was implemented by the Ministry of Economy and Competitiveness. This policy measure was part of the National Plan for R+D+I 2008-2011[467] and its objective was to enhance the competitiveness of Spanish industry by promoting knowledge about and stimulating the development of new applications based on nanoscience, nanotechnology, material science and technology, and process technologies. Six themes were targeted: Nanotechnologies applied to materials and new materials in health sector, nanotechnologies for information and telecommunications, nanotechnologies in relation to industry and climate, smart materials with tailored properties based on knowledge as materials and performance coatings for new products and processes, advances in technology and materials processing, development and validation of new industrial models and strategies/new technologies for manufacturing design and process/network production, and exploitation of convergent technologies. The measure covered different lines such as supporting investments, projects, institutional strengthening, infrastructure and utilisation of knowledge, supporting first market operations for innovative products and access to early stage/development funding, system articulation and internationalisation and targeted public research organisations, SMEs and other companies.

Both in the last Spanish Strategy of Science, Technology and Innovation 2013-2020[468] and in the State Plan of Scientific and Technical Research and Innovation 2013-2016[469] (both dependent on the Ministry of Economy and Competitiveness), nanotechnology is considered a sector to be boosted when referring to Key Enabling Technologies (KETs), but there is not a strategic plan such as in previous periods.

Regional initiatives in Spain include:

- Estrategia Nanobasque (2008)[470]: To promote the implementation of micro and nanotechnologies in the Basque companies, the Basque Government designed a strategy called NanoBasque in 2007. On December 3 2008, the Department of Industry, Trade and Tourism of the Basque Government launched the nanoBasque Strategy in the framework of the Basque Science, Technology and Innovation Plan 2010. The nanoBasque Strategy was an initiative designed to develop a new economy sector enabled by nanotechnology. It was created with the purpose of covering three main areas of action, namely: company, knowledge and society. One of the objectives was to create a new model of relations to involve both national and international companies, scientific, technological, political and social agent. The expected result were targeting the efficiency and the integration of the ecosystem of innovation that was clearly aimed at the market, based on the co-operation between all parties. The launch of the nanoBasque Strategy was accompanied by the creation of a dynamic support agency, the nanoBasque Agency, with the mission of coordinating and managing the development of the Strategy. The nanoBasque Strategy strived to boost Basque the presence of companies and research agents on international nanotechnology initiatives and markets. EUR 550 million were expected to be mobilised in the 2009-2015 period, with a proportion of public funding of 52% on the total.
- Within the nanoBasque strategy and using CONSOLIDER funds, the Cooperative Research Center NanoGUNE was created with the mission of performing world-class nanoscience research for the competitive growth of the Basque Country, thereby combining basic research with the objective of boosting nanotechnology-based market opportunities and contributing to the creation of an enabling framework to remove existing barriers between the academic and business worlds.
- The Andalusian Centre for Nanomedicine and Biotechnology, BIONAND, is a mixed centre part owned by the Regional Ministry of Health and Social Welfare, the Regional Ministry of Finance,

[466] http://www.idi.mineco.gob.es
[467] Ibid
[468] http://www.idi.mineco.gob.es/stfls/MICINN/Investigacion/FICHEROS/Spanish_Strategy_Science_Technology.pdf
[469] http://www.idi.mineco.gob.es/stfls/MICINN/Investigacion/FICHEROS/Spanish_RDTI_Plan_2013-2016.pdf
[470] http://www.nanobasque.eu/aNBW/web/en/strategy/index.jsp

Innovation, Science and Employment and the University of Malaga. BIONAND has been co-financed, with a contribution of 70% of the total cost, by the European Regional Development Fund (ERDF) together with the Ministry of Economy and Competitiveness in the frame of The Spanish National Plan for Scientific Research, Development and Technological Innovation 2008-2011 (record number, IMBS10-1C-247, quantity. EUR 4.9m). The three main research areas are nanodiagnostics, therapeutic nanosystems, and nanobiotechnology.

- IMDEA-Nanociencia is a private non-profit Foundation created by the regional Government of the Community of Madrid in November 2006 to shorten the distance between the research and society in the Madrid region and provide new capacity for research, technological development and innovation in the field of nanoscience, nanotechnology and molecular design. Researchers at IMDEA Nanoscience are developing distinct diagnostic tools, including nucleic acid-based and nanoparticle-based sensors for detection of biological targets of medical interest, and magnetic nanoparticles to be used in medical imaging as high-sensitive contrast agents.

The United Kingdom (UK)

The main player in UK policy measures related to nanotechnology as a key enabling technology (KET) is the Department for Business, Innovation and Skills (BIS) and its agency, the Technology Strategy Board, now called Innovate UK[471]. It supports SMEs with high growth potential, manages the Small Business Research Initiative[472] and identified future potential growth sectors. Both institutions have also developed a number of measures facilitating the knowledge exchange and technology adoption, such as: commercialisation opportunities and Knowledge Transfer Partnerships, Knowledge Transfer Networks, Technology and Innovation Centres, and Small Businesses Research Initiative.

The main interest of the UK government for nanotechnology started in 2002, when they published the **Taylor Report**[473] which recognised that investment in nanotechnology was increasing rapidly worldwide. Following the Taylor Report, an announcement was made by Lord Sainsbury of GBP 90m of funding for the Micro and Nano Technology Manufacturing Initiative. This funding was committed between 2003 and 2007. **Micro- and Nano-technology Manufacturing Initiative** (MNT Initiative) were joint investments by the Government, the Regional Development Agencies (RDAs) and the devolved administrations of Wales and Scotland. The Initiative was launched to help the industry build on the expertise of the UK science base and win a share of this developing market, harnessing the commercial opportunities offered by nanotechnology.

Approximately one third of this investment went to Collaborative R&D MNT Projects, and two thirds to capital infrastructure. Generally built on existing university or business expertise, the twenty-four facilities were targeted at addressing a broad range of key application areas where micro/nano scale activity was considered key to future UK industry capability and where the UK had some strength. Micro/nano technologies were included within relevant broader collaborative R&D competitions, principally in the materials, medicine and electronics areas. In 2007 the **Nanotechnology Knowledge Transfer Network (NanoKTN)[474]** was created with the objective of supporting the exploitation and commercialisation of MNT through informing, linking and facilitating innovation and collaborations between users and suppliers of nanotechnology in order to build a strong MNT community in the UK. The centres were grouped into four main themes: nano-metrology; nanomaterials (including health and safety); nanomedicine; and nanofabrication. Between its creation and 2014 the NanoKTN secured about £82million for UK industry, mainly focussed on SMEs, providing a good return investment on the initial input of £3million. In 2014, NanoKTN was merged with another 15 KTN in the new organisation KTN Ltd.

In 2006, the Engineering and Physical Sciences Research Council issued its **Report of the Nanotechnology Strategy Group[475]** as an active response to the EPSRC 2005 Nanotechnology Theme Day Report that found that there were flaws in the structure for nanotechnology R&D in the UK. The report proposed, in conjunction with researchers and users, to identify a series of "grand challenges" in nano-science and nano-engineering, focused initially on areas such as energy, environmental remediation, the digital economy and healthcare, where an interdisciplinary, stage-gate approach spanning basic research through to application will be an integral part of the challenge of enabling nanotechnology to make an impact. The "grand challenges" were to be addressed via

[471] https://www.gov.uk/government/organisations/innovate-uk
[472] https://www.gov.uk/government/collections/sbri-the-small-business-research-initiative
[473] http://webarchive.nationalarchives.gov.uk/20130221185318/http://www.innovateuk.org/_assets/pdf/taylor%20report.pdf
[474] https://connect.innovateuk.org/web/nanoktn
[475] https://www.epsrc.ac.uk/newsevents/pubs/report-of-the-nanotechnology-strategy-group/

interdisciplinary consortia spanning the EPSRC research spectrum, and including collaboration with sister Research Councils (e.g. BBSRC).

In December 2007, the Research Councils announced a Cross-Council programme "**Nanoscience through Engineering to Application[476]**", with the objective of providing an additional GBP 50 million in areas where the UK nanotechnology research base could make a significant impact on issues of societal importance such as healthcare. These societal or economic Grand Challenges wanted to be addressed in a series of calls for large-scale integrated projects. They were led by the Engineering and Physical Sciences Research Council, in collaboration with stakeholders including other Research Councils, industry, the Technology Strategy Board (TSB) and the Nanotechnology Research Coordination Group.

Government announced its intention to develop a UK Strategy for nanotechnologies in its 2009 response to the Royal Commission on Environmental Pollution's report, Novel materials in the Environment: The case of Nanotechnology.

The **Nanoscale Technologies Strategy 2009-2012[477]** was launched in October 2009 by the TSB and targeted the ways by which nanotechnologies could address major challenges facing society such as environmental change, ageing and growing populations, and global means of communication and information sharing. Its objective was to provide the framework for future applied research predominantly through activity inspired by the needs of wider technologies and challenge-led calls.

In 2010, the Ministerial Group on Nanotechnologies, the Nanotechnology Research Co-ordination Group (NRCG), and the Nanotechnology Issues Dialogue Group (NIDG) issued the UK **Nanotechnologies Strategy - Small Technologies, Great Opportunities[478]**. This Strategy defined how Government will take action to ensure that everyone in the UK could safely benefit from the societal and economic opportunities that these technologies offer, whilst addressing the challenges that they might present.

In 2012 the Department for Environment, Food and Rural Affairs (DEFRA) launched the **Nanotechnology Strategy Forum (NSF)**[479] in order to facilitate discussion and engagement between Government and stakeholders in matters referred to the responsible advancement of the UK's nanotechnologies industries. The NSF is an advisory body formed by *ad hoc* expert with a membership drawn from industry, regulators, academia and NGOs (non-governmental organisations and it is jointly chaired by the Minister of State for Universities and Science (BIS) and the Parliamentary Under-Secretary for DEFRA and is supported by a small secretariat based in DEFRA.

The UK **Enabling Technologies Strategy 2012-2015**[480] also addresses four enabling technologies - advanced materials; biosciences; electronics, sensors and photonics; and information and communication technology (ICT) to support business in developing high-value products and services in areas such as energy, food, healthcare, transport and the built environment. Nanotechnology is identified as having a significant underpinning role across most of these technology areas, particularly in the healthcare and life sciences sectors.

[476] https://www.epsrc.ac.uk/newsevents/pubs/nanotechnology-programme/
[477] http://www.nibec.ulster.ac.uk/uploads/documents/nanoscaletechnologiesstrategy.pdf
[478] http://www.steptoe.com/assets/htmldocuments/UK_Nanotechnologies%20Strategy_Small%20Technologies%20Great%20Opportunities_March%202010.pdf
[479] https://www.gov.uk/government/groups/nanotechnology-strategy-forum
[480] https://www.gov.uk/government/publications/enabling-technologies-strategy-2012-to-2015

ANNEX 6: PRODUCTS FOR NANOTECHNOLOGY PHOTONICS

This Annex contains thirteen tables of products as follows:

- Diode lasers
- Light-emitting diodes (LEDs)
- Flat panel displays
- Anti-scratch coatings
- Optical and opthalmic coatings
- Organic light-emitting diodes (OLEDs)
- Microscopy
- Nano lithography
- Digital imaging sensors
- Add/drop filters
- Optical amplifiers (Op amps)
- Optical switches
- Other

Some use nanomaterials to improve light transmission/ optical properties (e.g. nanocoatings on surfaces of lenses) while others use nanotechnology within photonics technology (e.g. CNTs in diode lasers).

1 DIODE LASERS

Product Name	Description	Producer
Polarisation-Maintaining Mode-locked Fibre Laser (PFL-200)	Provides ultra-short pulse laser systems and solutions based on carbon-nanotube photonic technology.	Alnair Labs Corporation
Carbon Nanotube Femtosecond Laser	Provides ultra-short pulse laser systems and solutions based on carbon-nanotube photonic technology.	
Single Mode Laser Diodes	Quantum dot (QD) semiconductor lasers (emission wavelengths ranging from 1064 nm to 1310 nm and broad optical gain with a tuning range of 160 nm) based on indium arsenide quantum dots in gallium arsenide (InAs/GaAs) with an aluminium gallium arsenide (AlGaAs) barrier compound.	ELUXI
Comb-Laser	The comb-laser is a light source with a spectrum consisting of frequency equidistant lines, each corresponding to one longitudinal cavity mode. The uniqueness of the comb-laser comes from the number of its lines in conjunction with their superior individual temporal stability. An ordinary multi-frequency diode laser suffers from the mode-partition noise (MPN), resulting in extensive fluctuation in time of the spectral lines which hinder their applicability in optical communications. In contrast, the relative intensity noise (RIN) of each spectral line of a quantum dot comb-laser is low enough to carry broadband data without errors or signal disappearance. The compact monolithic comb-laser diode chip is based on InAs/InGaAs quantum dots in GaAs/AlGaAs.	Innolume

Product Name	Description	Producer
Single-mode laser diodes	Resonant cavity light emitting diode InGaAs/AlGaAs chips operating at 930nm, 960nm, 1170nm, 1240nm and 1270nm.	
Gain-chips (GC)	Gain-chip is a gain medium for building tuneable diode lasers or high stability external cavity diode lasers. Gain-chip is similar to a laser diode chip except the it has a deep anti-reflecting coating (on one or both facets) which significantly increases the threshold of self lasing or eliminates it.	
FemtoCut	Near-infrared (NIR) femtosecond laser pulses for ultraprecise intracellular and intra-tissue surgery, cell isolation and nano-structuring of biomaterials well, as for high-resolution multiphoton tomography.	JenLab GmbH
MPTflex	For clinical *in vivo* optical biopsies with subcellular spatial resolution based on near infrared femtosecond laser technology for: melanoma detection, diagnostics of dermatological disorders, tissue engineering, cosmetic research, skin aging, in situ drug monitoring, animal research studies, stem cell research, and detection of fluorescent proteins.	
1240-1310nm quantum dot lasers	Quantum dot lasers	QD Laser, Inc.
1300nm high temperature quantum dot lasers	Quantum dot lasers	

2 LIGHT-EMITTING DIODES

Product Name	Description	Producer
Nanowire light-emitting diodes (nLEDs)	Nanowire light-emitting diodes (nLEDs) based on proprietary hetero-structured semiconductor nanowire epitaxial growth and process technologies, for which standard manufacturing equipment and materials can be utilised.	glō AB
Superluminescent Diodes (SLD, SLED)	Similar to a laser diode, a super luminescent light emitting diode is based on an electrically driven pn-junction that, when forward biased, becomes optically active and generates amplified spontaneous emission over a wide range of wavelengths. The peak wavelength and the intensity of the SLD depend on the composition of the active material and on the injection current level. SLDs are designed to have high single pass amplification for the spontaneous emission generated along the waveguide but, unlike laser diodes, insufficient feedback to achieve lasing action. This is obtained through the joint action of a tilted waveguide and anti-reflection coated facets.	Innolume
RCLED & LED	Resonant cavity light emitting diode InGaAs/AlGaAs chips operating at 930nm, 960nm, 1170nm, 1240nm and 1270nm.	
LED phosphors	LED phosphors for white LEDs	Phosphor Technology Ltd.
Quantum Light™	Quantum dot-based white LEDs	QD Vision

3 FLAT PANEL DISPLAYS

Product Name	Description	Producer
LW9500	LG has named the new LED technology Nano because it is a very slim film. Using nano holes, LG has enabled local dimming and ensured that no clouding or bleeding occurs. With local dimming a screen can control light output in zones on the panel to enable extremely deep black levels and a high contrast ratio. LG can now create very slim TVs with a full LED backlight.	LG
55LM960V	See above	
47LM960V	See above	
55LW980T	See above	
47LW980T	See above	
65LA970W	See above	
55LA970W	See above	
LG 47LW980W TV	Flat screen TV LG Nano LED TV with smart TV functions	
Pioneer® Organic Electroluminescent	OEL — Organic Electroluminescent-displays were introduced by Pioneer in 1999. OEL displays have advantages over normal displays, as the display can be read from wide angles and even in bright sunlight and, given that it is easier to read, it is also easier use in vehicles so the driver can keep their eyes on the road longer. A self-emitting device, backlighting is not required. It is power efficient.	Pioneer
TCL H9700 55'' Television	Color IQ technology is an advanced light emitting semiconductor technology developed by QD Vision, Inc. By integrating QD Vision's Colour IQ™ optical component with customers' display technologies, TVs and monitors achieve full colour for a more natural and vivid viewing experience. Color IQ is made of quantum dots, which provide the red and green light.	QD Vision
TCL H9700 65'' Television	See above	
Hisense K7100 55'' Television	See above	
Philips E6 27'' Monitor	See above	
Philips 6850 55'' Television	See above	
Emissive Projection Film	Reputedly the world's first Emissive Projection Display (EPD), a full-colour, high-definition video display on a fully transparent screen offering a wide viewing angle. The optically clear, emissive screen is made by coating a layer of fluorescent nano-material on PET film. With this display, a glass window in any building or the windscreen of a vehicle can be converted into a digital display without blocking the view, or be used for high-contrast projection display and TV applications in a bright environment.	Sun Innovations

4 ANTI-SCRATCH COATINGS

Product Name	Description	Producer
Uvex supravision sapphire	Lenses coated with Uvex Supravision Sapphire are extremely scratch-resistant and highly resistant to chemicals. The lacquer system features nanotechnology to considerably increase the non-stick properties of the lens making them easier to clean. Water-based and oily marks can be removed effortlessly.	Uvex Arbeitsschutz GmbH
ZEISS PureCoat® PLUS	Plastic lenses help make glasses lighter and more comfortable, but are much more prone to scratches than glass lenses. The scratch-resistant technology in PureCoat® PLUS protects lenses from scratches.	Zeiss AG

5 OPTICAL/ OPTHALMIC COATINGS

Product Name	Description	Producer
B+W 46MM XS-PRO VARIO ND MRC NANO	Camera filter Multi-Resistant Coating (MRC): this nano-coating is protective outer layer on all XS-Pro Digital MRC filters. The nanotechnology-based characteristic (lotus effect) produces a better beading effect with water, making cleaning simpler and faster than ever before. MRC nano has an improved outer (8th) layer over regular MRC. MRC by B+W is not only an effective multiple layer coating, it is also harder than glass, so that it protects filters from scratches and it is also water and dirt repellent, thus facilitating filter maintenance.	B+W
B+W 30.5mm XS-Pro Clear MRC-Nano 007	As above	
B+W 86MM XS-PRO CLEAR MRC-NANO 007	As above	
B+W 49MM XS-PRO UV MRC-NANO (010M)	As above	
B+W 49MM XS-PRO KSM C POL MRC-NANO	As above	
B+W 4 x 6 GRADUATED ND MRC NANO (701M)	As above	
B+W 30.5MM XS-PRO HTC KSM CPOL NANO	Camera filter The B+W HTC Kaesemann C-Pols, in F-Pro and thin XS-Pro mounts, are the latest polarisers from B+W. HTC stands for High Transmission Circular Polariser, with a 1-1.5 stop loss, as opposed to up to 3 stops with standard polarisers.	
Fujifilm XF 56 mm/1,2 APD	Camera lens A large-diameter medium-telephoto prime lens.	Fujifilm

Product Name	Description	Producer
	The fast F1.2 lens produces creamy bokeh (the blur produced in the out-of-focus parts of an image) while its 56mm focal length offers a comfortable shooting distance. X-Series cameras have won a solid reputation for their faithful reproduction of skin tones and combining them with this lens delivers the ultimate portrait photography results. The built-in APD filter produces even smoother bokeh, making the subject stand out even more and enhances creativity, for portraits and other subjects.	
Nikon 300mm f 2.8 ED-IF AF-S VR NIKKOR	Camera Lens Super-fast telephoto AF-S lens with Vibration Reduction (VR) and Nano Crystal Coat.	Nikon
Nikon AF-S NIKKOR 24mm f 1.4G ED	Nikon's Extra-low Dispersion (ED) glass ensures sharpness and contrast even at larger apertures, and an exclusive Nano Crystal Coating (N) reduces the lens flare and ghosting typically seen with wide-angle lenses.	
Nikon Lenses	Fast-aperture, high performance wide-angle zoom optimised for FX and DX-format sensors and features Nikon ED Glass and Nano Crystal Coat.	
Nikon Coolpix P3/P4	Nano Crystal Coating	
Nikon AF-S VR 105 f 2.8G IF-ED	An anti-reflective coating developed by Nikon that virtually eliminates internal lens element reflections across a wide range of wavelengths.	
Panasonic Lumix DMC FZ200	The Nano Surface Coating boasts an extremely low reflectance ratio and it is applied to the DMC-FZ200 for exceptional optical performance with clarity by minimising flaring and ghosts.	Panasonic
Lumix TZ-35 (16MP, 20x Optical Zoom, 3 inch LCD Screen) SuperZoom Compact Digital Camera- Black	Camera. The Nano Surface Coating is applied for clarity with minimum flare and ghost.	
DMC-GF3X	Camera with nanosurface coating	
HC-X800 3MOS FULL HD-video camera	New F1.5, 29.8mm Leica Dicomar lens surface with nanotechnology.	
H-X025 Interchangeable lenses	Camera Lens Surface treatment with nanotechnology significantly reducing ghosting and flare	
DMC-GF5X	Camera with nanosurface coating	
HC-X900 3MOS FULL HD-video camera	F1.5, 29.8 mm Leica Dicomar lens surface with nanotechnology.	
DMC-GX1X	Camera with nanosurface coating	
H-PS14042 Interchangeable lenses	Surface treatment with nanotechnology significantly reducing ghosting and flare	
DMC-FZ150 - Digital camera	Camera. Surface treatment with nanotechnology, significantly reducing ghosting	

Product Name	Description	Producer
	and flare	
H-PS45175 Interchangeable lenses	Surface treatment with nanotechnology, significantly reducing ghosting and flare	
DMC-FZ48	Camera with nanosurface coating	
Sony - SEL70200G	Camera Lens Cutting edge optical technologies, including Nano AR Coating and Super ED and ED glass elements, combine to deliver high lens performance.	Sony
Sony - SAL500F40G	Camera Lens. A Nano AR Coating minimises flare, eliminates opacity and tightens blacks. Effectively suppress reflections that can cause flare and ghosting with Sony’s original Nano AR Coating technology. This regular nano-structure allows accurate light transmission, contributing to high-quality images, even more so than lenses with coatings that use an irregular nano-structure. The reflection suppression characteristic of the Nano AR Coating is superior to conventional anti-reflective coatings, providing a notable improvement in clarity, contrast, and overall image quality.	
Sony - SAL300F28G2	Camera Lens Effectively suppress reflections with Sony’s original Nano AR Coating technology. This precisely defined regular nano-structure allows accurate light transmission, contributing to high-quality images, even more so than lenses with coatings that use an irregular nano-structure. The reflection suppression characteristic of the Nano AR Coating is superior to conventional anti-reflective coatings, providing a notable improvement in clarity, contrast, and overall image quality.	

6 OLEDs

Product Name	Description	Producer
REVEL GCM	OLED Grid Ceiling Mount	Acuity Brands Lighting, Inc
REVEL HCM	OLED Hard Ceiling Mount	
TRILIA	OLED Ceiling Mount TRI / STR Units	
NOMI	OLED Straight and Curve Wall Sconces	
CANVIS VRT / VTM	OLED Pendant/Wall Mount Screen / Pose	
KINDRED WM	OLED Wall Mount	
CANVIS HRZ / HZM	OLED Pendant Mount Drape / Twist	
KINDRED PM	OLED Pendant Mount	
ASON'S OLED	ASON'S OLED emits light with little colour change independent of an angle.	
OLEDs	Low power consumption	ASON Technology Co. Ltd.
AMBER OLED	Large surface emission	Lumiotec
BRITE FL300	Very thin structure	OLEDWorks GmbH

Product Name	Description	Producer
BRITE FL300L	Smooth light (can view the light source directly)	
Lumiblade	OLED lighting system	Philips Lighting
VELVETM OLED	"The merits of VELVETM OLED lighting, when compared to traditional lighting, are numerous:	Verbatim Americas, LLC.

7 Microscopy

Product Name	Description	Producer
Cypher S	Cypher™ Atomic Force Microscope uses a third generation NanoPositioning System (NPS™) With positioning accuracy better than 60 picometres in X, Y and Z, the most accurate measurements, positioning and nano-manipulation are possible.	Asylum Research
MFP-3D Infinity	The Asylum Research MFP-3D Infinity™ is the most advanced AFM in the MFP-3DTM family. It combines higher performance, powerful capabilities, and a new system architecture designed for future expansion.	
MFP-3D Origin	The MFP-3D Origin™ marks the intersection of performance and affordability in the Asylum Research MFP-3D™ AFM family. It has leading closed-loop AFM resolution and performance, diverse applications, such as for polymers (morphology and nanomechanics), electronic devices and other advanced materials (e.g. nanoscale failure analysis)	
MFP-3D-Bio	The Asylum Research MFP-3D-BIO™ sets the standard for integrating AFM and optical microscopy for bioscience research. Good AFM imaging resolution, force measurement performance and application versatility while seamlessly integrating with a full range of optical techniques.	
Dimension FastScan	The Atomic Force Microscope benefits from enhanced Nanoscale Automation. Bruker's new AutoMET™ software enables the combination of high-resolution AFM imaging with fast, automated metrology. It provides exceptional ease of use and adaptability for critical-to-quality measurements in high-volume measurement applications.	Bruker Nano Surfaces
Dimension FastScan Bio AFM	The Dimension FastScan Bio™ Atomic Force Microscope (AFM) breaks long-standing barriers to provide routine high-resolution research of biological dynamics, with temporal resolution up to three frames per second for live sample observations	
Dimension Icon-Raman	High Performance AFM with co-localised micro-Raman capability. The Dimension Icon AFM-Raman system, consisting of the Icon AFM and a research-grade confocal Raman microscope (Horiba, LabRam, etc.), is on a single, rigid, anti-vibration platform. This configuration allows the system to maintain each individual instrument's full functionality, providing optimum combined performance.	
MultiMode 8	Industry standard AFM for high-resolution imaging. Providing high-resolution imaging and	

Product Name	Description	Producer
	quantitative material property mapping. Delivering multimode versatility. World's most published AFM. Powered by PeakForce Tapping technology to provide new information, faster results, and greatly improved ease of use. New quantitative material property mapping is made possible using PeakForce QNM®, which analyses each tip-sample interaction to extract nano-mechanical properties including modulus, adhesion, deformation, and dissipation.	
Flex-ANA — AFM for force mapping	For fully automated nano-mechanical data acquisition and analysis. Key features and benefits include real-time, automated data collection and analysis, proprietary algorithm to cope with large variations in sample height, and is ideal for nano-mechanical testing and force mapping of soft, rough, and sticky samples.	Nanosurf AG
Flex-Axiom — AFM for materials research	Flex-Axiom is an Atomic Force Microscope for materials research. It has measurement capabilities in air and liquid, versatility in applications and modes, compatibility with inverted microscopes and high precision scanning and data acquisition capability.	
Flex-Bio — AFM for life science	Flex-Bio is an Atomic Force Microscope for life science, which offers Seamless integration with inverted microscopes, advanced force spectroscopy investigations and correlate fluorescence, topology and biomechanical properties in a single package.	
FluidFM — Nano and cell manipulation	FluidFM is a Nanofluidic tool for single-cell biology and next-level nanomanipulation. It has a Unique combination of AFM with Cytosurge FluidFM® technology Optical view of the sample and highly accurate pressure, force, and position control and can access unique experiments: cell adhesion and spectroscopy mapping, single-cell manipulation and analysis, deposition and lithography even in liquid, injection and extraction, etc.	
LensAFM — AFM for optical microscopes	Extends the resolution of upright microscopes or 3D profilometers. Key features and benefits: Mounts on virtually every upright optical microscope or 3D optical profilometer; Integrated motor for automated cantilever approach and engage; Standard and extended AFM modes available through a modular controller.	
NaioAFM — AFM for small samples	All-in-one atomic force microscope for small samples and education purposes. Key features and benefits: ready-to-use, table-top AFM; controller, scan head, airflow shielding, vibration isolation, camera, and sample positioning integrated into a single device; all standard AFM operating modes available; simple cantilever exchange: no adjustments required.	
NaniteAFM — AFM for large samples	Compact and mountable atomic force microscope for large-sample measurements. Key features and benefits: compact and robust atomic force microscope for stand-alone and large stage operation; easy and quick cantilever exchange and alignment reduces	

Product Name	Description	Producer
	downtime; automated batch measurements and scripting interface for system integration.	
Park HDM Series	The task of identifying nanoscale defects is a very time consuming process for engineers working with media and flat substrates. Park NX-HDM is an AFM system that speeds up the defect review process by an order of magnitude through automated defect identification, scanning and analysis. Park NX-HDM links directly with a wide range of optical inspection tools, thus significantly increasing the automatic defect review throughput. It provides accurate sub-angstrom surface roughness measurements, scan after scan.	Park Systems Corp.
Park NX-Bio	Life scientists want to see how biological materials look like at nanoscale resolution and how soft they are in liquid and buffer conditions. Park NX-Bio enables that with its innovative in-liquid imaging Scanning Ion Conductance Microscopy (SICM) and its highly acclaimed AFM technology.	
Park NX-Hivac	Park NX-Hivac allows failure analysis engineers to improve the sensitivity of their measurements through high vacuum Scanning Spreading Resistance Microscopy (SSRM). Because high vacuum scanning offers greater accuracy, better repeatability, and less tip and sample damage than ambient or dry N2 conditions, users can measure a wide range of dope concentration and signal response in failure analysis applications.	

8 Nanolithography

Product Name	Description	Producer
FleXform-ADC™	Complete development kit for flexible hybrid electronics. The FleXform-ADC is designed for developing and prototyping printed and/or flexible sensors integrated with physically-flexible ICs.	American Semiconductor Inc. (US)
FleX™	FleX™ Silicon-on-Polymer is a process for creating high-performance, single-crystalline CMOS with multi-layer metal interconnect on a flexible substrate.	
AMONIL®: High performance UV nanoimprint resist	Based on the extensive long lasting experience in the field of nanoimprint AMO developed an UV-curable resist (AMONIL®) and a matching adhesion promoter (AMOPRIME) which are commercially available.	AMO GmbH Gesellschaft für Angewandte Mikro- und Optoelektronik GmbH
Large Area Nanogratings	AMO offers gratings fabricated by in-house interference lithography (IL). The IL technology allows producing large, coherent and periodic gratings with nearly constant pitch. Pattern transfer and further processing can be carried out according to customer requirements.	
OptiStack® lithography system	Enabling the progression of Moore’s law beyond 20 nm, Brewer Science® OptiStack® systems are used for advanced lithography.	Brewer Science, Inc. (US)
EVG®510HE	Semi-automated hot embossing system	EV Group GmbH (AT)

Product Name	Description	Producer
EVG®520HE	Semi-automated hot embossing system	
EVG®750	Automated hot embossing system	
EVG®750R2R	Automated hot embossing system	
EVG®620	Automated mask alignment system	
EVG®6200	Automated bond alignment system. Wafer-to-wafer alignment for subsequent wafer bonding applications.	
IQ Aligner®	The IQ Aligner µ-CP System allows for micro-moulding and nano-imprinting processes with stamps and wafers from 150 mm to 300mm diameter.	
EVG®770	Automated NIL Stepper is designed for step and repeat large area UV-Nano-imprint Lithography (UV-NIL) processes compatible for 100 mm up to 300 mm wafers.	
EVG®720	Automated UV nano-imprint lithography system	
EVG®7200	Automated UV nano-imprint lithography system	
HERCULES®NIL	UV-NIL Track System	
PhableR 100	Photolithographic Tool	Eulitha AG (CH)
MultiView 4000	Providing up to four AFM systems in one, the MultiView 4000 system is a novel platform for the most advanced experiments in nanoscale transport, optical pump-probe, and read-write lithography. Access to multiple probes enables non-destructive characterisation, manipulation and measurement of electrical, thermal, and optical properties of materials and electronic devices. With up to four probes that can be operated simultaneously and independently, the MV 4000 is a nanoscale probe station with feedback and scanning capabilities.	NANONICS IMAGING Ltd.
Photonic Professional GT	The next generation 3-d laser lithography system, Photonic Professional GT for 3-d microprinting and maskless lithography. It combines two writing modes in one device: an ultra-precise piezo mode for arbitrary 3-d trajectories (FBMS) and the high-speed galvo mode (MBFS) for fastest structuring in a layer-by-layer fashion. In combination with the software package, the system is embedded best along the 3D printing workflow and offers a high degree of automation. In addition, the Photonic Professional GT allows for the fabrication of high-resolution photo masks and other direct write applications.	Nanoscribe GmbH
Vistec SB3050 series	The Vistec SB3050 series - now with a Cell Projection option - is designed to meet the challenges of direct patterning down to the 32nm technology node and features Variable Shape Beam (VSB) technology with vector scan and continuously moving stage principles for throughput optimisation.	Vistec Electron Beam GmbH
Vistec SB351 system	The Vistec SB351 system has been developed for the 90nm node and features the 65nm R&D capability node. Thanks to its modular system architecture the SB351 Variable Shaped Beam	

Product Name	Description	Producer
	system is used for both mask making (incl. nanoimprint) and direct write. Fully automatic substrate handling and network-supported operation software allow production, prototyping and R&D work. Further highlights of the Vistec SB351 are the full 300mm wafer exposure capability and the fast data preparation software including Proximity Effect Correction.	
Vistec SB250 electron beam lithography system	The Vistec SB250 electron beam lithography system has been designed as a universal and cost-effective tool for both direct write and mask making applications to allow the customers to react quickly to market demands. With its 210 x 210mm stage travel range it is the ideal tool for exposing masks up to 7 inch and wafers up to 200 mm diameter.	
Vistec SB254	The Vistec SB254 is a high performance, universal and cost effective electron-beam lithography system (Variable Shaped Beam/Cell Projection optionally), enabling the usage for both direct write and mask making for a large variety of applications in industry and applied research.	

9 Digital Image Sensors

Product Name	Description	Producer
Graphene-based photodetector	The worldwide fastest graphene-based photodetectors. By demonstrating a maximum data rate of 50 GBit/s, a new record level could be reached, pushing this technology closer to applications.	AMO GmbH
SCAN300FL	The SCAN300FL digital x-ray imaging device provides the full benefit of a direct conversion x-ray sensor using Ajat's custom charge integration CMOS. Fast frame read-out with extremely low noise level, matches the requirements for low-contrast/high sensitivity scanning applications. The sensor is also well suited for high SNR applications using integrated digital frame accumulation techniques. The very high efficiency Cd(Zn)Te-CMOS sensor technology provides excellent image quality with x-ray energies up to 300 kVp, but can also operate on low energies starting from 10 kVp. SCAN300FL incorporates an active Peltier element for controlling the temperature within +-0.1 degrees for maximal performance. The system also includes specialised calibration software for high performance imaging.	Ajat Oy
DIC100TH (Unique Tube to Tube sheet weld inspection system)	The DIC100TH (Dynamic Imaging Camera for inspection of welds in heat exchangers) digital x-ray imaging device provides the full benefit of a direct conversion x-ray sensor using Ajat's custom charge integration CMOS. Fast frame read-out with extremely low noise level, matches the requirements for low-contrast/high sensitivity applications and specifically this product is a unique solution for	

Product Name	Description	Producer
	inspecting welds in heat exchangers	
SCAN5000TDI	Utilising the SCAN5000TDI (link) sensor family a cost effective and highly performing scanning linear array can be implemented with active area of 450mm that can scan-image the chest or other body parts at 40cm/sec with 0.1mm line width (i.e. 4000lines/sec TDI output). Since this is a linear rather than a full format array, the cost of such sensor is highly competitive against flat panels, while CdTe/CdZnTe offers high image quality, sensitivity and contrast.	
PID350	In nuclear medicine (PET, SPECT) as well as bone densitometry, the PID350 (link) technology family offers energy dispersive imaging with high position resolution and heralds a new generation of such systems.	
SNAP225 (Cd-Zn-Te-CMOS dental sensor)	The SNAP225 is a compact digital x-ray imaging device which provides the full benefit of a frame mode direct conversion x-ray sensor with asymmetric active area using Ajat’s charge integration CMOS. This unique sensor combines three functionalities in one and is intended for integration into dental panoramic, cephalometric and local 3-d/CT systems. These functionalities are achieved utilising AJAT’s reconstruction and image processing software available to OEMs as part of the sensor package.	

10 Add/ Drop Filters

Product Name	Description	Producer
Low-Power 100 Gb/s Optical Engine	Kotura's silicon photonics platform supports optical engines using Wave Division Multiplexing(WDM), in which different signals can share the same path. As the only silicon photonics provider to offer WDM, Kotura's optical engine provides distinct advantages, including reducing the cost of fibre and associated connectors within the interconnect fabric for 4x25 GHz solutions by a factor of four, as well as readily expanding from four channels to eight, 16 or even 40 channels over a single strand of optical fibre. Additionally, Kotura's silicon photonics platform also supports optical engines using parallel fibre channels.	Kotura (Mellanox Technologies)

11 Optical amplifiers (op amps)

Product Name	Description	Producer
Semiconductor Optical Amplifiers	Semiconductor optical amplifiers (booster optical amplifiers) are amplifiers which use a semiconductor to provide the gain medium. They have a similar structure to Fabry–Perot laser diodes but with anti-reflection design elements at the end faces. Recent designs include anti-reflective coatings and tilted waveguide and window regions which can reduce end face reflection to less than 0.001%.	Innolume

Product Name	Description	Producer
	Since this creates a loss of power from the cavity which is greater than the gain, it prevents the amplifier from acting as a laser.	
Transceiver Ics	SiFotonics has developed a series IC integrating Laser/VSCEL driver, limiting amplifier (LA) and MCU into a tiny 5mm x 5mm QFN32 package for active optical cable (AOC) applications, to settle the package size limitation in traditional SFP+. It can be used not only for traditional SFP+, PON SFP+ but also suitable to be used in AOC which require small size package.	SiFotonics Technologies Co., Ltd.
Ge/Si APD	SiFotonics Ge/Si avalanche photodiodes use separate absorption, charge and multiplication (SACM) structure to achieve excellent absorption efficiency, high gain and low noise factor, simultaneously, benefitting from high responsivity of germanium to near-infrared light and low k-factor of Si as multiplication layer. SiFotonics Ge/Si APDs have lower temperature dependence owing to incorporating Si as avalanche material, compared with traditional InP or InAlAs materials, and is able to operating over a wide temperature range from -40°C to 85°C.	
Ge/Si PIN PD	Germanium-on-silicon technology in near-infrared (0.8um to 1.6um) photodiodes, instead of InGaAs material, for the fields of telecommunications, metro networks and FTTHs. This technology has an overwhelming superiority in mass production and uniformity, owing to compatibility with CMOS manufacturing process. SiFotonics Ge/Si PIN photodiodes have been optimised for best performance, including high responsivity, fast response, low capacitance and low bias voltage. The product portfolio covers speeds from 10 Gb/s to 25 Gb/s. All SiFotonics Ge/Si PD devices can be customised, including optimal wavelength, data rate, array size and array pitch.	
APD TO/ROSA	SiFotonics offers small and hermetic germanium-on-silicon avalanche photodiodes in TO-can/ROSA packages for the easy and suitable installation in data communications and telecommunication systems.	

12 Optical switches

Product Name	Description	Producer
LightLEADER 4000	LightLEADER 4000 Platform	LYNX Photonic Networks
APS4300	Optical Module for 1+1 Unidirectional Protection	
APS4301	Optical Module for 1:1 Fibre Link Protection	
APS4305	Optical Module for 1+1 Fibre Link Protection	
APS4305-E	Optical Module for 1+2 Fibre Link Protection	
APS4310	Optical Module for single-ended bi-directional protection. For fibre link, equipment and dual homing protection applications	

Product Name	Description	Producer
APS4301-D	Dual 1:1 protection switching module for bidirectional fibre links	
APS4325-B	Dual bi-directional fibre-links protection module with embedded bypass switching	
LightLEADER 4301-i	Protection and bypass system for intermediate network sites	
APS4300B-HP	A high-power optical module for 1+1 unidirectional protection	
LightLEADER 3201/3202/3212	Optical add-on protection system for WDM bi-directional fibrelinks	
LightLEADER 4301-i	Protection and bypass system for intermediate network sites	
LightLEADER 3002-U	Optical bypass protection switch for 2 circuits	

13 Other

Product Name	Description	Producer
ZERODUR Zero Expansion Glass Ceramic	ZERODUR is an inorganic, non-porous glass ceramic, characterised by a phase of evenly distributed nanocrystals within a residual glass phase. ZERODUR contains about 70-78 weight% crystalline phase with a high quartz structure. This crystalline phase has a negative linear thermal expansion, while that of the glass phase is positive. The crystals have an average size of about 50 nm.	Advanced Optics SCHOTT AG
ZERODUR® K20	ZERODUR® K20, a low thermal expansion version of ZERODUR®, has been optimised to withstand higher application temperatures. The material is white in colour and offers good IR transmittance of between 3.5 and 5 microns and homogeneous high reflectivity properties. The non-porous ZERODUR® K20 exhibits good polishing abilities and excellent vacuum properties, and can be delivered as small high-precision optical components.	
nOPTO	ALD for optical and photonics applications, coating objects that are difficult or impossible to coat by other methods, enabling engineering of novel optical materials. The accuracy of the film thickness in ALD is usually 0.2 to 12 angstroms, depending on the material. ALD coatings are completely conformal and pinhole-free, making them especially suitable for barriers and passivation layers.	Beneq Oy
FDTD Solutions 8.12	FDTD Solutions is a 3-d Maxwell solver, capable of analysing the interaction of UV, visible, and IR radiation with complicated structures employing wavelength scale features. Rapid prototyping and highly-accurate simulations reduce reliance upon costly experimental prototypes, leading to a quicker assessment of design concepts and reduced product development costs. FDTD Solutions are for diverse application areas, from fundamental photonics research to current industrial applications in imaging, lighting, biophotonics, photovoltaics, and many more.	Lumerical Solutions, Inc.

Product Name	Description	Producer
CMOS Photonics™ technology	Luxtera's CMOS Photonics™ technology allows the construction of complex optical systems in production CMOS processes – the same processes currently used for building VLSI circuits. Luxtera has designed, fabricated and tested a complete suite of photonic elements that when combined with high speed digital circuits enable the delivery of a broad range of disruptive computer, communications and sensing products.	Luxtera
Nano-optic Isolator	SubWave Optical Isolator, a family of high-performance, nano-enabled optical isolators to reduce both overall cost and device size for data communication and telecommunication transceivers and transponders. They can either be used in standard transceiver designs, or as the basis for more compact new architectures. They use a proprietary nano-based design to directly integrate a polarisation function on the surface of a garnet Faraday rotator, thereby creating thinner isolator cores - as thin as 0.5mm or less, a reduction of over 30% compared to traditional isolator designs - and so enabling physically smaller isolators (c. 0.5mm x 0.5mm) depending on the application. This nano-lithography-based manufacturing methodology is being used to produce surface mount, cylindrical mount and magnet-less isolators.	NanoOpto Corp (part of API Nanotronics)
SubWaves IR Cut Filter	SubWave Infrared Cut-off Filter (IRCF). Designed for high performance, high volume digital imaging applications, including compact digital camera modules, NanoOpto's SubWave IRCF increases the crispness and colour saturation of digital images. The SubWave IRCF implements NanoOpto's proprietary nano-optic design principles to produce a device with high transmission of visible wavelengths, a sharp cut-off at the boundary with the rejection region, high rejection of infrared wavelengths, and a very low edge shift. In combination, these performance attributes enable improved digital image quality. The SubWave IRCF is available diced to customer specific sizes, and as 100mm x 100mm sheets.	
Deep Ultraviolet Polarisers	API's nano-grating-based optical technology is able to manage UV over the areas required to process large wafers. The proprietary deep-UV optical nano-products are manufactured at API Nanotronics' nanofabrication and MEMS facility, NanoOpto, which includes one of the world's largest multi-wafer atomic layer deposition production capabilities.	
Polarising Beam Splitters/Combiners	The devices are used to combine light from two input beams into a single output beam (PBC mode) or to separate the orthogonal polarisation components of an input signal into two output beams (PBS mode). These advanced optical devices are optimised for operation at either 1310 nm or 1550 nm. NanoOpto's PBS/C are nanofabricated directly on thin glass substrates using proprietary processes, resulting in a product with a small form factors	

Product Name	Description	Producer
	and shape and size versatility, in contrast to conventional large crystal PBS/C products. The NanoOpto devices can be produced (on substrates) with thicknesses ranging from 0.2 mm to 1.6 mm and sizes from 0.5mmX0.5mm to 15mmX15mm. The operating range is -40 to 80°C. Custom specifications and larger sizes are also possible. They have applications in telecom, scientific equipment such as Raman amplifiers, polarisation division Mux/DeMux, polarisation switches, variable optical attenuators, and general fibre networks.	
Optical Isolators	The SubWave Optical Isolator uses a proprietary nano-structure-based design to directly integrate a required polarisation function on the surface of a garnet Faraday rotator, thereby creating thinner isolator cores - as thin as 0.5mm or less, a reduction of over 30% compared to traditional isolator designs - and so enabling physically smaller isolators - on the order of 0.5mm x 0.5mm. Nano-lithography-based manufacturing is being used to produce surface mount, cylindrical mount and magnet-less isolators to meet customer application specifications. Individual SubWave Optical Isolator models support either the 1550nm (C-band) or 1310nm bands for telecomms and data communication applications.	
Waveplates, Retarders and Trim Retarders	SubWave AQWP650+, an achromatic quarter waveplate for high performance, robust, DVD/CD read/write combination drives with applications for entertainment, mobile systems and computing. This wideband achromatic waveplate improves performance, increases compactness, improves reliability, reduces assembly costs, and simplifies the design of DVD/CD read/write combination drives. The SubWave AQWP650+ can either be used in manufacturing as a drop-in replacement for existing quarter waveplates, or in design as the basis for more compact new optical pick-up unit architectures. The SubWave AQWP650+ uses a proprietary nano-structure-based design to provide zero order performance across a broad wavelength range. This device is constructed using only dielectric materials and exhibits stable optical performance and physical robustness over a broad operating temperature range.	
Microlens Arrays	Optical micro- and nano-sized lens arrays with 100% fill factor, a wide range of diameters and pitches, from deep submicron to tens of microns, made through conformal growth of dielectric monolayers onto pre-patterned templates by atomic-layer deposition (ALD). This method has a degree of freedom of choosing lens materials with a broad range of optical refractive indexes, as well as of controlling the curvature of the lens surface and the fill factor of the lens array.	
WDM Filters	WDM Filters	

ANNEX 7: HUMAN HEALTH AND SAFETY

INTRODUCTION

Nanoparticles used in photonic products are listed in the table on *Hazard bands for selected nanoparticles*.

The basis for the evaluation is the "Stoffenmanager Nano" application developed by TNO (Van Duuren-Stuurman, et al. 2012). In short, Stoffenmanager Nano is a risk-banding tool developed for employers and employees to prioritise health risks occurring as a result of respiratory exposure to nanoparticles for a broad range of worker scenarios. In absence of a comparable tool for consumer exposure, it will also be used for this type of exposure, inapplicable. "Stoffenmanager Nano" combines the available hazard information of a substance with a qualitative estimate of potential for inhalation exposure[481]. "Stoffenmanager Nano" does not contemplate the dermal and oral routes of exposure. The respiratory route is the main route of exposure for many occupational scenarios, while the oral route of exposure is considered minor and sufficiently covered, from a safety point of view, by good hygiene practices established in production facilities as prescribed through general welfare provisions in national health and safety legislation in EU countries (ECHA 2012). In view of the nature of the products in this sector, also oral exposure of consumers is considered to be minor. The dermal route may be the main route of exposure for some substances or exposure situations, and cause local effects on the skin or systemic effects after absorption into the body (ECHA 2012). However, nanoparticles as such are very unlikely to penetrate the skin (Watkinson, et al. 2013), and consequently nanospecific systemic toxicity via the dermal route is improbable. Therefore, when evaluating nanorisks for the respiratory route, the most important aspects of occupational and consumer safety are covered.

The hazard of six metal oxide nanoparticles has been reassessed and their hazard bands have been updated. This revision, which follows the hazard assessment methods established by van Duuren-Stuurman et al. (2012), but makes use of more recent toxicity data, has been published in a TNO-report (Le Feber, et al. 2014). Hazard bands for the nanoparticles listed the table *Hazard bands for selected nanoparticles* are taken by preference from this report and, if not available in that report, from van Duuren-Stuurman et al. (2012). If a nanoparticle in the list has not been evaluated in either publication, data were collected from public literature to derive its hazard band, as described below.

Hazard assessment of nanoparticles not previously assessed in Stoffenmanager Nano

Introduction

In "Stoffenmanager Nano" the available hazard information is used to assign specific nanoparticles to one of five hazard bands, labelled A to E (A= low hazard, E= highest hazard). As hazard banding has not previously been performed for all the nanomaterials of importance for the sector "Manufacturing", nanoparticle toxicity data have been collected and hazard bands derived for them here, according to the methodology described for "Stoffenmanager Nano" in van Duuren-Stuurman et al. (2012). In essence, it applies the toxicity classification rules of EU Regulation (EC) No 1272/2008 on classification, labelling and packaging (CLP) of substances and mixtures. The method is summarised in the diagram below.

[481] Currently version 1 of Stoffenmanager Nano is being updated with recent data and insights.

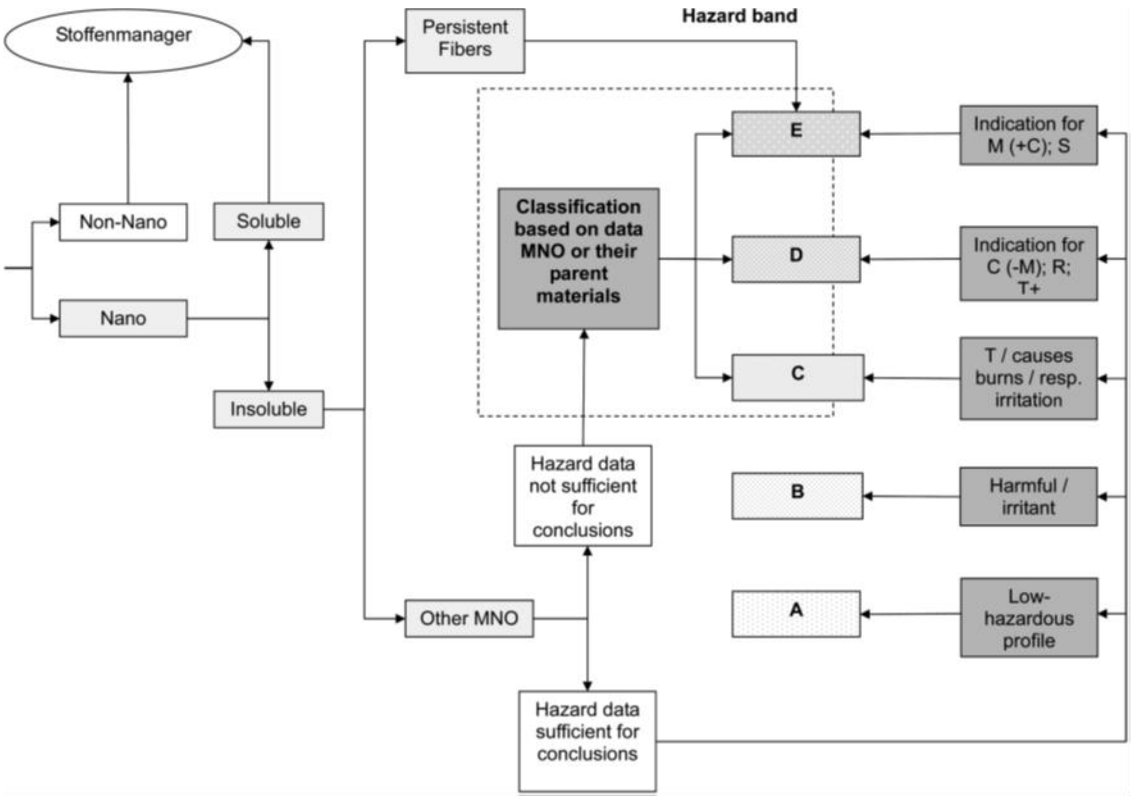

Figure 1: The stepwise approach of hazard banding of Stoffenmanager Nano (Van Duuren-Stuurman, et al. 2012)

C = carcinogenic, +C = and carcinogenic, M = mutagenic, -M = and not mutagenic, MNO = manufactured nanoparticle, R = reprotoxic, resp. = respiratory, T = toxic, T+ = very toxic Stoffenmanager refers to the non-nano version of Stoffenmanager as described by Marquart et al. (2008).

Gallium nitride

No toxicity data are available on gallium nitride nanomaterials (Proust, et al. 2002). On the ECHA Classifications and Labelling web pages, gallium nitride is labelled as Skin Sensitiser Category 1[482]. In absence of data, gallium nitride is not classified for any other property. Based on its parent compound's classification as skin sensitiser, gallium nitride nanowire is assigned to hazard band E.

Germanium

Very few toxicity data are available for germanium nanoparticles. Ma et al. (2011) report an LC_{50} of approx. 1.3 μM in a MTT test using CHO K1 cells and water soluble germanium nanoparticles with allyamine-conjugated surfaces. No classification and labelling data on (non-nanoform) germanium are available at the ECHA classification and labelling website[483]. The available information is too little to assign a hazard band.

Graphene

Graphene is composed of sp^2-hybridisedcarbon atoms arranged in a two-dimensional structure. The various forms of graphene include few-layer graphene, reduced graphene oxide, graphene nanosheets and graphene oxide (GO) (Seabra, et al. 2014).

The UK government body, the Medicines and Healthcare Products Regulatory Agency (MHRA), and the US Food and Drug Administration (FDA) are now reviewing all forms of graphene and functionalised graphene oxide (GO) because of their poor solubility, high agglomeration, long-term retention, and relatively long circulation time in the blood (Begum et al. 2011 cited in Nezakati, et

[482] http://echa.europa.eu/information-on-chemicals/cl-inventory-database/-/cl-inventory/view-notification-details/5411/37371832
[483] http://echa.europa.eu/information-on-chemicals/cl-inventory-database

al. 2014).

Currently, limited information about the in vitro and in vivo toxicity of graphene is available (Seabra, et al. 2014). The toxicity profiles of graphene and graphene oxide (GO) nanoparticles remain difficult to separate, since their characterisation, bulk and chemical composition are very similar at the nanometre length scale (Nezakati, et al. 2014).

In vitro graphene has been demonstrated to be cytotoxic, be it overall to a lesser degree than carbon nanotubes (Seabra, et al. 2014). However, the reliability of this conclusion can be doubted since Seabra et al. stated that graphene showed an inverse dose-relationship, being more cytotoxic than carbon nanotubes at low concentrations. The only elaborate comparative study reported by Seabra et al., refers to genotoxicity towards human fibroblast cells. GO proved to be the most potent genotoxic agent compared to iron oxide (Fe_30_4), titanium dioxide ($Ti0_2$), silicon dioxide ($Si0_2$), zinc oxide (ZnO), indium (In), tin (Sn), core—shell zinc sulphate-coated cadmium selenide (CdSe(3)ZnS), and carbon nanotubes.

Intratracheal instillation of 50 µg GO in mice caused severe pulmonary distress after inhalation causing excessive inflammation, while the amount of non-functionalised graphene instilled did not (Duch et al. 2011). Single intravenous (i.v.) injection of graphene oxide into mice at a dose of 10 mg/kg bw accumulated in the lung resulting in pulmonary oedema and granuloma formation, with NOAEL of 1 mg/kg bw (Zhang, et al. 2011). Furthermore, surface functionalised graphene (PEGylated) appears to be far less toxic: no toxic effects after single i.v. injection of 20 mg/kg bw (Yang, et al. 2011). In mice, PEGylated GO materials showed no uptake via oral administration, indicating limited intestinal absorption of the material, with almost complete excretion. In contrast, upon i.p. injection in mice, PEGylated GO was found to accumulate in the liver and spleen (Yang, et al. 2013 (cited in Seabra, et al. 2014)).

The toxicity of graphene is dependent on the graphene surface (the chemical structure or the nature of the functionalised coatings), size, number of layers, cell type, administration route (for in vivo experiments), dose, time of exposure, and synthesis methods (Seabra, et al. 2014). Generalisations are therefore hard to make, but graphene nanostructures are not fibre-shaped and theoretically may be assumed to be more safe than carbon nanotubes (Seabra, et al. 2014).

Based on the scarce available evidence, and in spite of its theoretical advantage in relation to carbon nanotubes, it cannot be excluded that some forms of graphene will be as potent a toxicant as carbon nanotubes. Therefore, graphene is assigned to hazard band E.

Overview of hazard bands of nanoparticles in the sector

The table below presents an overview of selected nanoparticles of the sector and their hazard bands, either taken from le Feber et al. (2014) or van Duuren et al. (2012), or derived in this report in paragraphs above.

Table 1 Hazard bands for selected nanoparticles

Nanoparticles	Hazard Band	Source
Gallium nitride nanowires	E	This report
Graphene	E	This report
Silicon dioxide (silica), crystalline	E	van Duuren et al. (2012)
Silicon dioxide (silica), synthetic amorphous	C	le Feber et al. (2014)
Single-walled carbon nanotube (SWCNT)	E	This report
Titanium dioxide (titania, rutile, anatase)	B	le Feber et al. (2014)

Exposure Assessment

Photonics includes the generation, emission, transmission, modulation, signal processing, switching, amplification, and detection/sensing of light. The commercial applications of nanotechnology in the field of photonics include: lasers and parts thereof, nano-engineered photonics materials, communications & all-optical signal processing, and nanoscale functional imaging and spectroscopy. Products for the sector photonics range from communication technology such as Low-Power 100 Gb/s Optical Engine by Mellanox Technologies and Rings of fire by HP to laser devices such as the Comb-Laser by Innolume. Research institutions and academia do play a visible role in this sector as producers (to some extent of prototypes).

Based on the provided overview of commercially available products, engineered nanomaterials are present in the products as part of a matrix. No free solids or liquids containing engineered nanomaterials, which can become airborne during the use-phase, were listed. During the production of these photonic products, employees can be exposed to free engineered nanomaterials. However, as many of these activities are performed on a R&D scale, exposure to engineered nanomaterials will be relatively low. In conclusion, the use of photonic nano-products results in an exposure band 1 (consumers and workers), whereas during the production of photonic products an exposure band 2 (workers) is believed to be realistic.

Risk Assessment

The hazard and exposure bands are combined to yield so called priority bands, according to the scheme depicted in the chart. A high priority implies that it is urgent to apply exposure control measures or to assess the risks more precisely, and a low priority implies that it is not very urgent to apply exposure control measures ort to establish the risk involved with more precision. It should be emphasised that because of the scarcity of available information, the scheme is set in a conservative way (according to the precautionary principle).

Table 2 Priority bands in the Stoffenmanager

Hazard band / Exposure band	A	B	C	D	E
1	3	3	3	2	1
2	3	3	2	2	1
3	3	2	2	1	1
4	2	1	1	1	1

Risks based on the hazard and exposure banding applied to the photonics sector are listed in the table below.

Table 3 Priority bands nanotechnology photonics sector

		Exposure Band	
		Production Phase of ICT Product	Use and End-of-life Phase ICT Products
Nanoparticle	Hazard Band	**2**	**1**
Gallium nitride nanowires	E	1	1
Silicon dioxide (silica), synthetic amorphous	C	2	3
Silicon dioxide (silica), crystalline	E	1	1
Single-walled carbon nanotube (SWCNT)	E	1	1
Titanium dioxide (titania, rutile, anatase)	B	3	3

There is a high risk to workers and consumers from gallium nitride nanowires, crystalline silica and single-walled carbon nanotubes, with respect to use and production. Furthermore, there is a moderate risk to workers from amorphous silica and a low risk from the use and production of titania and from the use of amorphous silica and titania.

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This report offers a snapshot of the environment for nanotechnology in the context of photonics. It gives an overview of policies and programmes for nanotechnology and photonics in the EU (and wider), publications, patenting, research & innovation, industry, products and markets, and the wider environment. The report is part of a series of eight NanoData Landscape Compilation studies covering the application of nanotechnology in the fields of construction, energy, environment, health, ICT, manufacturing, photonics and transport.

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