3D NANO-MANUFACTURING AND NANO-METROLOGY

TNO innovation for life

TNO.NL

CONTENTS

Introduction 5

3D NANOMANUFACTURING

Fast and flexible scanning probe 3D nano-patterning 9
Advanced atomic layer deposition (ALD) processes 10
High-throughput thermal nanolithography 11
Multi material additive manufacturing (3D printing) for metamaterials 12
STED lithography for manufacturing 3D nanostructures 14

3D OPTICAL NANOMETROLOGY

X-ray metrology 16
Interferometric nanoparticle detection 17
Meta-instrument for high throughput nearfield microscopy 18
Ptychography 19
Optical nearfield and optical metasurface technologies 20

3D NANOTOMOGRAPHY

High-throughput 2D arrays of miniaturised AFM 22
Photo thermo acoustic imaging of buried structures 24
Parallel, high throughput AFM 25
Subsurface ultrasonic resonance force microscopy 26

Subsurface scanning probe microscopy using electrostatic actuated cantilever 28
Nano-mechanical forces in scanning probe microscopes 30
Measuring distances with nearfield heat radiation 31
Measuring the tip-sample interaction forces in tapping mode AFM 32
Characterizing electron beam induced damage in metrology and inspection of advanced devices 34

ADVANCE MOTION CONTROL AND DYNAMICS
Nano-precision multi-agent maglev positioning platform 36
High bandwith, picometer resolution nanopositioning stage for metrology applications 38
3D profile measurement of high aspect ratio nanostructures 39
Automated cantilever exchange and optical alignment for high-throughput, parallel atomic force microscopy 40

CROSS OVER USE CASES
Bio-nanomedical instruments 42
Viruscan - indentification and characterization of viruses from their nano-mechanical properties 44

3D NANO-MANUFACTURING AND NANOMETROLOGY

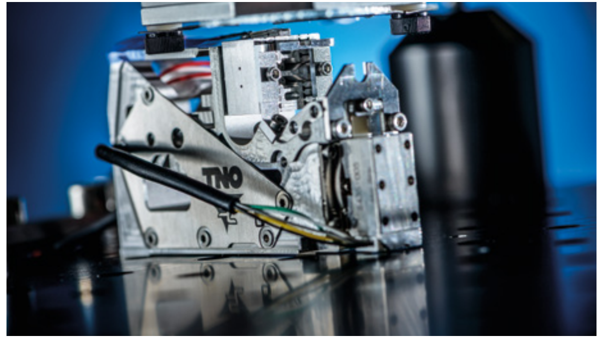
Further scaling and miniaturization of nanodevices (nanoelectronics, Quantum devices bio-nano devices for healthcare) brings major manufacturing, metrology and characterization challenges that cannot be met anymore by current techniques. The High Volume Manufacturing industry requires, more than ever, metrology methods that routinely measure structural and material parameters at atomic level in nm-sized structures, with atomic precision, with high throughput, for an ever increasing set of combinations of new materials in 3D structures.

The research program 3D nanomanufacturing will enable the transition from 2D to 3D nanostructures, that will support the need for ever more powerful devices. The focus is on the development of instruments and techniques which enable manufacturing and metrology of nanostructures at the very high speeds, accuracies and reliabilities required for industrial applications.

Introduction of 3D architectures (3D NAND, 3D X-Points, vertical and horizontal Gate All Around (GAA) Nanowires requires a breakthrough in the metrology and characterization process potentially based on a hybrid 3D nanometrology. Classical techniques and instruments do not provide a resolution at the required feature size and the required capabilities to resolve dimensional and material properties in 3D.

The Research program 3D nanomanufacturing consists of 4 main technology platforms. The technology platforms are:

- *3D Nanomanufacturing*
  The target of this technology platform is to develop concepts and instruments for nanopatterning, nanomanufacturing and nanomanupulation of structures below 10 nm. Examples are scanning probe nano lithography which enables, mask-less patterning of structures with sizes down to few nanometers. Other example is development of instrument based on STimulated Emission Depletion (STED) lithography which enables fabrication of 3 dimensional structures in resist, without a mask, with dimensions much smaller than the optical diffraction limit.

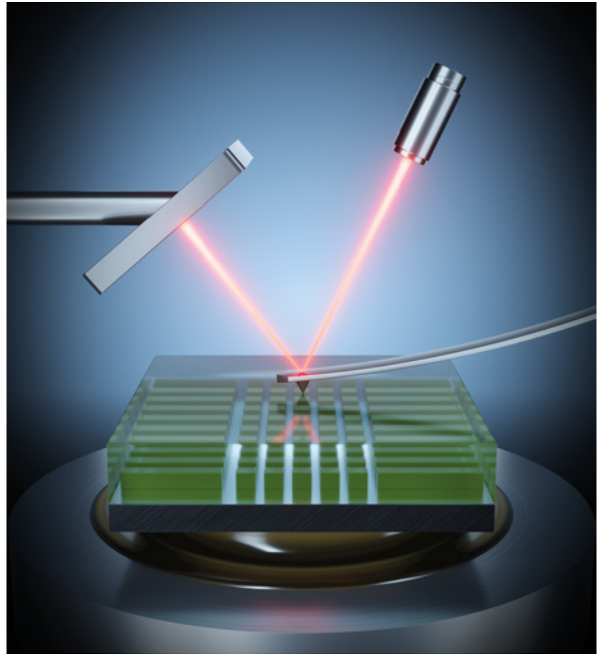


- *3D optical Nanometrology*
  In this technology platform, several optical techniques have been investigated to go further than the classical optical resolution limit. Most of existing optical technologies rely on fluorescence or switching on /off of certain molecules. In nanoelectronics industry working with fluorescence is not feasible, since these materials are not allowed in the semiconductor manufacturing industry. Therefore a couple of alternatives have to be found and investigated. Examples are nearfield optical microscopy with the use of Super Oscillatory concepts, Solid Immersion concepts and Quantitative phase computing methods.

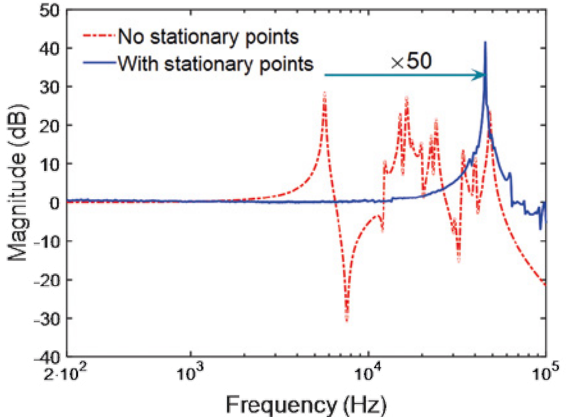
- *3D Nanotomography*
  In this technology platform, we develop techniques to characterize the mechanical and chemical properties at nano-scale in 3D.

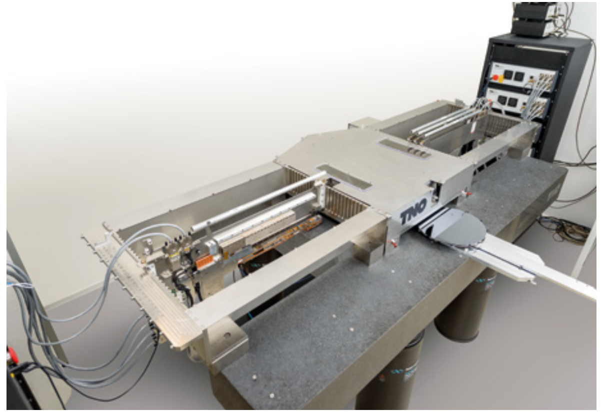
  Nondestructive subsurface nano-imaging is of tremendous importance due to the growing complexity of manufacturing nanotransistors, displays and solar cells. For example, today's 3D transistors such as FinFET, gate-all-around silicon nanowire FET, 3D NAND memory and future quantum electronics have nanostructures which are deeply buried beneath other nanostructured layers. The ability to manufacture, measure these structures on top of each other directly impacts chip's performance and yield. In this technology platforms we develop concepts and solutions to be able to:
  - Characterize chemical, mechanical properties at nano-scale
  - Nano-scale imaging of features or defects through several layers
  - Nano-scale imaging of full 3D profile of high aspect ratio structures

Examples are development of Subsurface Probe Microscopy (SSPM), to image nanostructures buried under various layers, and Photo-thermo-Acoustic Imaging, a fully optical method to measured 3D structures below the surface with depth sensitivity.



– *Advance motion control and dynamics*
For any nanomanufacturing and nanometrology instruments, higher speed vs higher accuracy is the typical tradeoff at the design phase. However, industrial demands require both specifications to be elevated beyond the current limits. This, in turn, brings a lot of challenges that can only be achieved with better control and dynamics design to utilize the maximum performance the instrument can offer.
In this technology platforms, novel dynamics and control methods are being developed to increase the throughput of instrument while maintaining a very high precision.





– *Cross over use cases*
Besides the main technology platforms of the program which target the primary used-cases of nanoelectronics, several cross-over used cases are being developed. Examples are development of techniques and instrument for characterizations of bio samples at small scales. Targets are personalized treatment to the patients, ultra-early detection of cancer and identifying viruses.

Hamed Sadeghian,
Scientific leader ERP 3D Nanomanufacturing

FAST AND FLEXIBLE SCANNING PROBE 3D NANO-PATTERNING

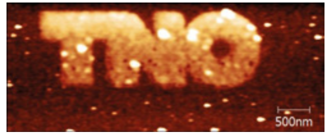
TECHNOLOGY:
Quantitative nano-scale 3D writing and pattern modification using scanning probe techniques by controlling tip-sample interaction forces at the nano-scale. By tuning the tip-sample interaction forces, writing performance can be changed and tuned for the sample of interest.

COMPETITIVE ADVANTAGE:
– Versatile technique for nano-pattern writing (e.g. nanostructures) without mask
– Cost efficient modification method in support of sensitivity studies (e.g. EUV mask errors)
– Knowledge and control of tip-sample interaction dynamics
– Simultaneous inspection and modification

APPLICATION AREAS:
– Enables sensitivity studies in support of EUV lithography system optimization
– Easy and fast writing of nano-patterns (e.g. nanostructures)
– Patterning of contact holes and via’s in any arbitrary pattern
– EUV Mask Repair
– Maskless 3D nano-patterning on structures

PROVEN SPECIFICATIONS:
– Patterning shown on different types of materials (Silicon, glass, PMMA, TaN, Metal Oxide)
– Feature resolution of ~50 nm achieved
– Patterning depth of approx. 35 nm achieved (on TaN)

TARGET SPECIFICATIONS:
– Feature size: 10- 200 nm
– Patterning depth of 100 nm
– Patterning depth accuracy of 0.1 nm



TNO logo patterned in glass

ADVANCED ATOMIC LAYER DEPOSITION (ALD) PROCESSES

One way of opening up the process window and thus the applicability of (spatial) ALD, is to stimulate the characteristic half-reaction rates in every ALD cycle. In exploratory research Energy-enhanced ALD has been reported and is explored today, in particular plasma-assisted, electron beam-assisted and laser-assisted (in short: energy-enhanced) growth of mostly binary compound layers or layer stacks.

Energetic beam(s) can be utilized for (local or global) surface modification, precursor adsorbate stimulation, etc., to form or perform novel materials at reduced temperatures, (pre-)patterned layers, selective area growth, even 3D-structures and new functionalities.

APPLICATION AREAS

'Direct write' deposition of Transparent Conductive Oxides (TCOs) and other functional materials for solar cells with increased efficiency, displays, etc.; SERS-based sensing (down to single-molecule detection); superlense beyond diffraction limit for biomedical imaging, optical lithography and data storage.

PROVEN SPECIFICATIONS

A first 'direct-write' demo was presented by us for Area-Selective ALD of In2O3:H, a promising TCO material. Line patterns with 0.6 -3 mm resolution were achieved by locally activating the surface using a µ-plasma printer, followed by ALD.

TARGET SPECIFICATIONS

Line patterns of < 100 nm resolution to be achieved with EBL pre-treatment.

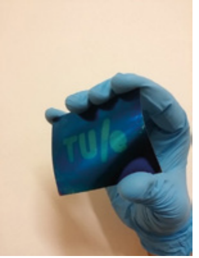


Figure 1. Logo created by direct-write ALD of 35 nm thick In2O3:H on flexible steel foil covered with 20 nm a-Si:H.

First demo of the capability of direct-write ALD for large-area and flexible electronics.

HIGH-THROUGHPUT THERMAL NANOLITHOGRAPHY

TNO and SwissLitho AG are developing a high-throughput, mask-less nanopatterning solution for nanostructures down to few nanometers using thermal scanning probe lithography (t-SPL).

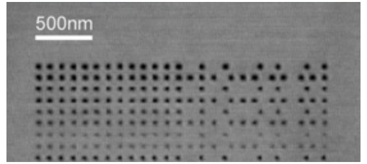
- Short time-to-feature for R&D applications
- Nanopatterning on wafers and samples with pre-defined pattern, without any mask
- Nanopatterning of many locations simultaneously
- 10 nm patterning resolution
- In-situ closed loop metrology of patterned features

Highly flexible nanolithography for process development and R&D

A Proof-of-principle setup has been built to show compatibility of the SwissLitho thermal SPL and the TNO parallelization technologies and with this setup we have shown similar performance as the SwissLitho instruments. Next step is the implementation of a non-contact, in-situ closed loop metrology, which is required for industry applications.

- Very short time-to-feature
- 10 nanometers half pitch
- 2 nanometer vertical resolution
- 2.5D write capability
- no vacuum required
- In-situ overlay measurement and alignment
- Compatibility with various pattern transfer processes and materials

High throughput 2.5D Thermal nanolithography is a very promising technology for flexible nanopatterning applications, where cost of Ownership of EUV lithography cannot be justified.



Features manufactured with t-SPL: contact holes

MULTI MATERIAL ADDITIVE MANUFACTURING (3D PRINTING) FOR METAMATERIALS

Multi-material additive manufacturing (also called Multi-material 3D printing) is used to engineer a metamaterial, which is able to selectively deposit the relevant materials at a high enough resolution. The layer-by-layer printing allows the design freedom required for metamaterials. Metamaterial requirements are in reach, however, resolution and material portfolio for 3D printing are limiting factors.

COMPETITIVE ADVANTAGE

- Design freedom required for metamaterials
- Vat photopolymerisation allows for higher resolution printing than other 3D printing technologies
- Vat photopolymerisation has a higher printing speed than other 3D printing technologies
- Conductive materials like silver paste are available from screen printing technology

APPLICATION AREAS:

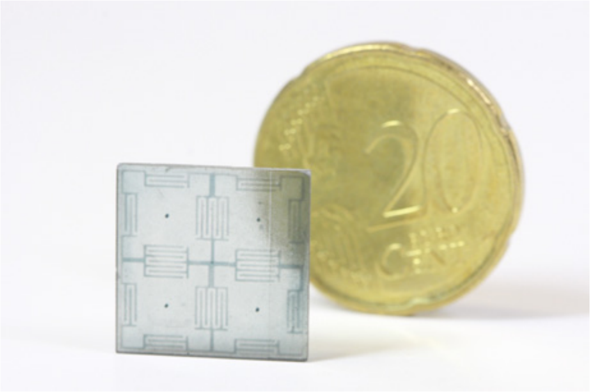
- Metamaterials, for example lenses with optical properties that go beyond conventional lenses and mirrors
- Embedded electronics, for example 3D printed circuit boards

PROVEN SPECIFICATIONS:

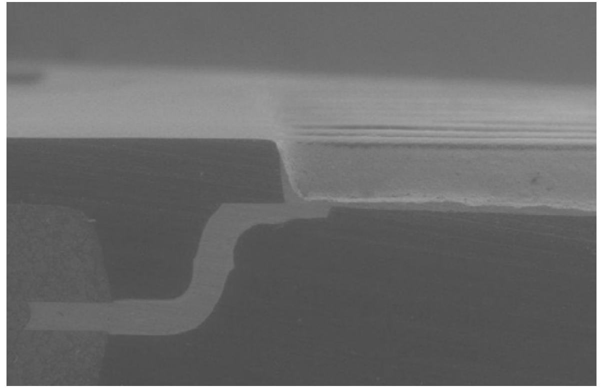
- 2½-dimensional conductive tracks have been produced in laboratory setting with a conductivity equal to 10% of copper bulk conductivity
- A structure is designed and printed as a metamaterial for electromagnetic waves at a specific wavelength
- A multi-material structure was successfully made at structure sizes of 200 µm

TARGET SPECIFICATIONS:

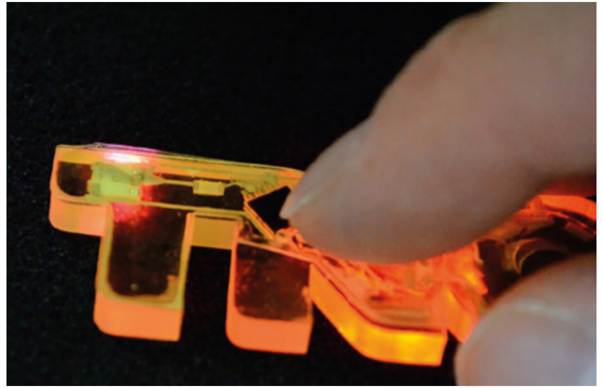
- Process development for multi-material additive manufacturing with structures of 100 µm using vat photopolymerisation
- Free form embedded conductive tracks and making significant steps towards copper bulk conductivity
- Low loss factor materials allowing the production of active array antenna systems typically used for telecommunications and radar applications
- The Lepus Next Gen machine for large area multimaterial vat photopolymerisation for large area printing with a resolution of 20 micron



Embedded polymer-polymer tracks.



SEM photo of conductive track connecting to electrical component



Printed product with embedded electronics including an LED

STED LITHOGRAPHY FOR MANUFACTURING 3D NANOSTRUCTURES

STimulated Emission Depletion (STED) lithography is a way to expose 3 dimensional structures in resist, without a mask, with dimensions much smaller than the optical diffraction limit. This is achieved by a first 'exposure beam', with a diffraction limited Gaussian spot to initialize the formation of material, followed by a second 'depletion beam'. This second beam has a donut like intensity distribution and stops the material formation of the 'exposure beam', resulting in an effective exposure volume, much smaller than the Gaussian intensity distribution.

Current state of the art 3D lithography is performed by 2 photon polymerization, but the resolution of this technique is still limited to 70% of the classical diffraction limit. With STED lithography the ultimate resolution depends on the parasitic exposure effect of the "depletion beam" that increases when the resolution will be improved. In literature resolutions down to 1/5 of the diffraction limit have been reported.

In state-of-the-art academic STED research, writing speed is severely limited by the chemical initialization and depletion processes. Current research foremost focusses on alternative chemical processes that enable orders-of-magnitude faster throughput.

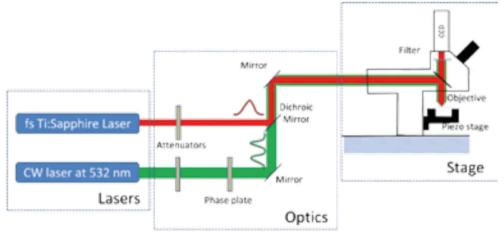
Applications are envisioned in the fundamental research market, where a 3D printer for nano-scale is usefull and in the application together with larger scale production technologies, where the STED is used in the local functionalization on nano-scale.

- Fast high resolution STED for research;
- Localized 3D deposition of functional material in/on existing microstructures:
  - Forming of metal tracks on 3D surfaces,
  - Functionalization of sensing layers on nano-scale,
  - Small optical interconnects in addition to larger-scale mask less lithography.

The combination of a diffraction limited Gaussian spot and a donut beam, resulting in an effective illumination spot that is significantly smaller than the diffraction limit of the optical system.

Calculations show writing speeds up to 1 mm/s should be well within the possibilities. Current research aims to verify the chemical performances experimentally. Upon confirmation of the chemical performance, testing of the writing speed is planned.

3D resolution of 100x100x100 nm with a writing speed of 1 mm/sec.



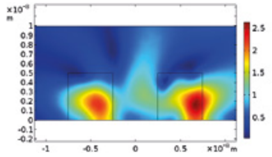
Schematic overview of the STED setup, using two lasers in the same optical path to activate and quench the formation process

X-RAY METROLOGY

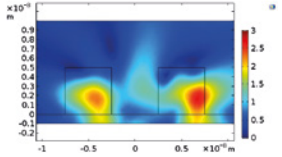
Optical metrology for Semiconductor applications is reaching the limits at the currently readily available wavelengths. The lasers that are user as light sources, and the high numerical aperture lenses that are being used, are designed up to 193nm (DUV). Sources with shorter wavelengths are soft x-ray or EUV sources. Optical elements for these light sources are usually mirrors systems because there are no materials with suitable optical properties available. The reflective elements that are used for beam shaping and focusing at these short wavelengths cannot be used to achieve high nummerical apertures (NA), severely limiting the achievable resolutions.

COMPETITIVE ADVANTAGE

Within this research, lensless imaging and reconstruction techniques are investigated that could outperform current DUV and classical x-ray imaging solutions.



Scattered field computed with analytic background field



Scattered field computed with numerical background field

Comparison between the analytical and numerical results of the scattering of a grating structure

An additional component of the research is to develop simulation tools to understand the x-ray - matter interactions and align them with existing imaging and reconstruction algorithms. The tooling would be an essential part of incorporating a-priori knowledge into the reconstruction algorithms.

APPLICATION AREAS

Optical metrology for semiconductor applications.

PROVEN SPECIFICATIONS

For Ptychography, a lens less image reconstruction technique, a separate setup has been built in visible wavelengths to investigate the algorithm performance

INTERFEROMETRIC NANOPARTICLE DETECTION

One of the key challenges in detecting the presence of a nano-particle on a substrate is to differentiate between the light scattered by the particle and the light scattered due to inherent surface roughness of the substrate. We developed a measurement technique, differential binary-phase interferometric particle detection, that allows to amplify the light scattered by the particle without equally amplifying the light scattered by the substrate.

COMPETITIVE ADVANTAGE

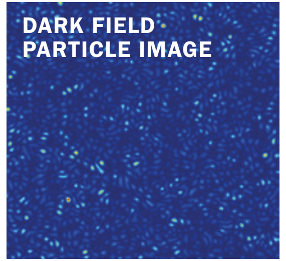
Compared to traditional methods, the proposed technique allows to detect smaller particles (~15 nm compared to >20 nm). This gain comes at the cost of being more sensitive to the aberrations of the imaging optics.

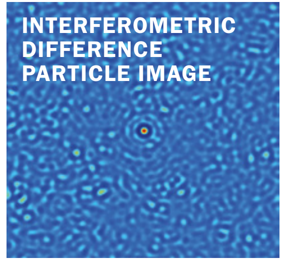
APPLICATION AREAS

1 Qualification of unpatterned blanks for EUV masks during production in order to prevent particles buried under the multilayer stack.
2 Scanning of witness samples on the presence of particles in order to qualify the cleanliness of semicon equipment

TARGET SPECIFICATIONS

Detection of sub 20 nm PSL particles on a smooth silicon surface (150x150 mm), with less than 1% particles missed and less than 10 false positives. This all within ½ a day.





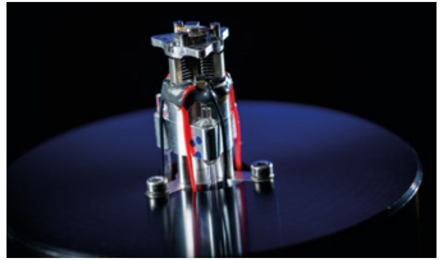
Simulated image of 15 nm particle on a substrate with 0.15 nm (rms) surface roughness using differential binary-phase interferometric particle detection.

META-INSTRUMENT FOR HIGH THROUGHPUT NEARFIELD MICROSCOPY

Recently, new optical elements offer the promise of beyond diffraction limit imaging. These elements often need to be positioned in the nearfield of a surface (<100nm). The Meta-Instrument was developed to offer the speed and accuracy for these applications.

COMPETITIVE ADVANTAGE

- Non-contact
- High resolution (in principal, down to 10 nm)
- High throughput
- Flexibility on the scanned location



APPLICATION AREAS

- High-resolution imaging of wafers, masks, large substrates
- Semiconductor metrology and inspection
- Bio-medical high resolution microscopy
- Patterned as well as unpatterned substrates

PROVEN SPECIFICATIONS

- Going beyond diffraction limit (0.3)
- Bandwidth of measurement: 10 kHz
- Accuracy of positioning of lens: 2 nm
- Vertical range: up to 1 mm

TARGET SPECIFICATIONS

- Below 10 nm resolution
- Bandwidth increase to 100 kHz
- Performing real imaging down to 60 nm resolution
- >300 measurements on a wafer, results in full scanning in one minute
- Scan size: 300 mm wafer

PTYCHOGRAPHY

Ptychography is a ‘lens less imaging’ technique that allows to characterize the three-dimensional shape of an object. Because no optical elements are required between the object and the detector, it can be used at short wavelengths for which no (practical) high numerical optics exist, such as x-rays.

COMPETITIVE ADVANTAGE

Significant improvement of the attainable resolution compared to more traditional optical methods.
Non-contact 3D metrology.

APPLICATION AREAS

Three-dimensional metrology for semicon.

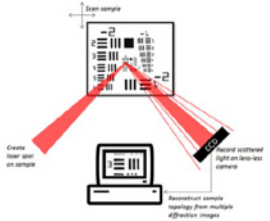
PROVEN SPECIFICATIONS

A test setup has been built to investigate the performance and sensitivities of ptychographic systems. Measurements have been performed and are now being processed. Complimentary to the experiments, a series of simulations were performed for an isolated study of different sensitivities and to assess the performance of various reconstruction algorithms. Image reconstruction down to 30nm resolution can be done reliably. Using a priori knowledge should be able to improve these numbers significantly.

TARGET SPECIFICATIONS

EUV ptychography:
A resolution in three dimensions of 20 nm with the prospect for improvements down to <10 nm.
The measurement time for a 10x10 μm area should be less than 25 sec.

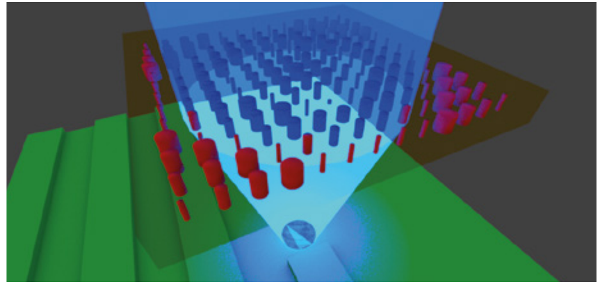
Visible-range test bench:
Diffraction limited imaging at a numerical aperture of 0.3
Lens less imaging of a 3D partially transparent sample.



Schematic representation of ptychographic measurement and reconstruction

OPTICAL NEARFIELD AND OPTICAL METASURFACE TECHNOLOGIES

Nearfield effects occur if an optical element is placed in subwavelength distance to the surfaces which will be inspected. In the nearfield more spatial frequencies are excited than usually propagate to the farfield detector. Nearfield optics makes use of these so called evanescent waves leading to higher resolution.



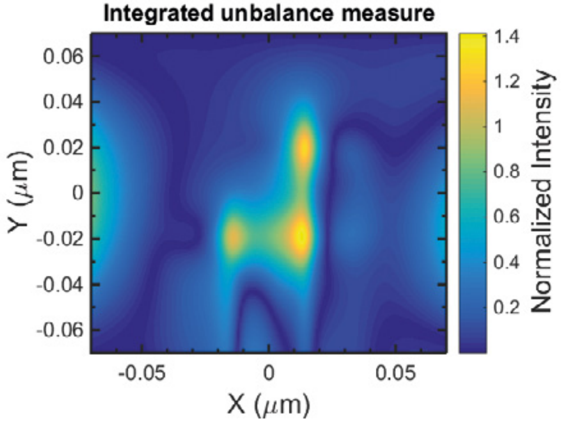
3D model of a dielectric resonator lens with the incident and transmitted light.

The nearfield effect enables various optical implementations. Within the conducted research, the following implementations are being investigated:

- Solid Immersion Lens (SIL). This is a small, hemispherical lens with a high refractive index, positioned under a high NA objective. The SIL lens is positioned within the nearfield of the surface to be imaged. Through the high refractive index lens very close to the surface undertest the numerical aperture (NA) of the lens is increased by a factor equal to the refractive index of the SIL. This means that a SIL microscope can achieve, in theory, a resolution which is substantially higher than the one of a conventional microscope.
- Nano antenna's; these antennas are also placed in the nearfield of a surface to be imaged to pick up the evanescent waves. The antennas will amplify the scattered polarizations of the light and encode the near field information into their scattered field, enabling the information to be propagated into the farfield; where it can be captured. This means that a nano-antenna microscope can achieve, in theory, an order of magnitude better resolution than a conventional microscope.

OPTICAL METASURFACES

- These are arrays of very small dielectric nano resonators/scatterers (sub-wavelength dimensions) embedded in extremely thin transparent membranes to locally control the phase and/or the polarization of an incoming wave-front. The control of the light is achieved by controlling the transversal dimensions of the resonators, rather than the curvature of surfaces, as it is for conventional refractive lenses.



Simulation of a reconstruction made with nano-antennas amplification of three nano particles suspended in air without a substrate. These particles could be resolved using light at 800 nm wavelength.

Optical metasurfaces can in principle allow any form of wave-front manipulation with extremely thin membranes easy to be integrated in very compact imaging systems, or as functional surfaces for light control on opto-mechanical instruments. A few examples are: micro lenses, filters, polarizers, perfect absorbers, beam-shapers, dimers for enhanced spectroscopy.

- Semiconductor metrology;
- Maskless imaging;
- Microscopy;
- Multi-dimensional (spectro-polarimetric) imaging;
- Spectroscopy.

PROVEN SPECIFICATIONS

- For all the implementations, simulations have been used to gauge the possible performance. For higher TRL implementations, such as the SIL and the dielectric resonators, the results will be closer to the final performance than for the low-TRL implementation of the nano-antennas.

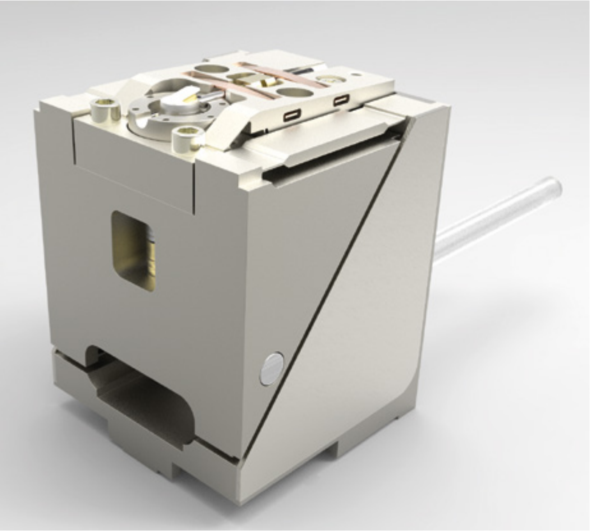
The target specifications depend on the application, but are mostly an imaging resolution below 100nm and capable of high throughput measurements.

HIGH THROUGHPUT 2D ARRAYS OF MINIATURIZED AFM

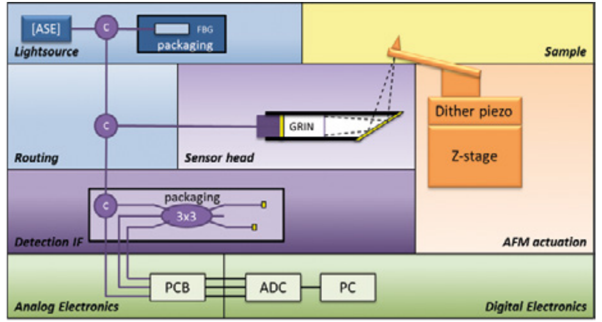
Following the successful realization of 1D parallel AFM concept, the next step is to further increase the throughput and flexibility. This is achieved with a new architecture, enabling 2D array of miniaturized AFM heads and removing the positioning arms. A further step towards higher throughput was made by decreasing the footprint of the scanhead to 26x26 mm2. Even further miniaturization was achieved by implementing a fiber interferometer for tip deflection detection. The same sensor is used to measure the z-displacement of the scanner, removing the uncertainty due to hysteresis in the piezo actuators.

Our strategy towards higher throughput and accuracy contains two focus areas:

– Miniaturized mechanics to improve dynamics behavior and enabling 2D array parallelization.
– Fiber interferometer with small sensor head and high dynamic range to measure both cantilever deflection and cantilever z-displacement.



CAD rendering of the miniaturized scan head



Schematic overview of the interferometric readout of the cantilever vibrations and displacement.

This strategy resulted in a designed scan head of 26x26mm and a z-stage with an expected Eigenfrequency of around 100 kHz. The fiber interferometric sensor combines the readout of the z-stage stroke and the AFM cantilever frequency up to approximal 1 MHz.

Further advantages of a large number of scan heads is that different kinds of measurements can be performed simultaneously.

APPLICATION AREAS

Metrology for semiconductor applications:

– The first targeted application is wafer and mask profile measurements.
– With further optimization it can be applied to other metrology areas, such as CD measurements.

PROVEN SPECIFICATIONS

The fiber interferometric readout, the main enabler of the miniaturization and improved accuracy, has been build and was shown to perform to specifications. The full hardware demonstrator of the scan head is being assembled.

TARGET SPECIFICATIONS

We target a true 2D matrix of miniaturized AFM heads with a repeatability in the height measurement of 0.5 nm. This is partly achieved by using a sensor for measuring the z-displacement directly on the tip itself. The balanced miniaturized mechanical design enables further improvement as the dynamic behavior allows higher control bandwidth.

PHOTO THERMO ACOUSTIC IMAGING OF BURIED STRUCTURES

Photo Thermo Acoustic Imaging (PTAI) uses a light pulse with a duration < 1ps to create an acoustic wave in a sample with frequencies in the range of 100 GHz. These high frequencies correspond to acoustic wavelengths below 100 nm, enabling measurements with depth resolutions below 100 nm.

The acoustic wavelength can be made significantly smaller than with traditional optical wavelengths, resulting in improved depth resolutions, even through optically opaque layers. Due to the mechanical nature of the acoustic waves this method allows the direct measurement of mechanical properties instead of the optical properties of the material.

APPLICATION AREAS:

- Detection of buried sub surface defects at the nano-scale,
- Measurement of alignment markers, buried under optically opaque layers

Thermo Acoustic Imaging test setup.

- Nanoscale depth profiling of the mechanical properties of (nanoporous) coatings,
- Means for GHz excitation of samples in combination with Sub Surface Probe Microscopy (SSPM).

PROVEN SPECIFICATIONS:

Shot-noise limited measurement of surface displacements, enabling picometer sensitivity at 50 kHz measurement frequency. Time traces (up to 300 ps) are measured by scanning a mechanical delay line.

TARGET SPECIFICATIONS:

Increase of the measurement frequency up to 250 kHz, in combination with a non-mechanical scanning to measure time traces.

PARALLEL, HIGH THROUGHPUT AFM

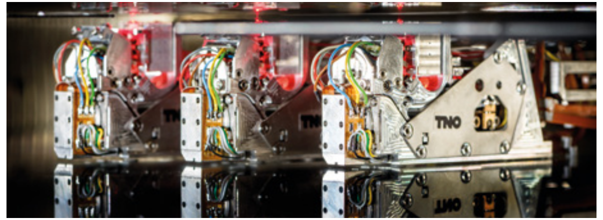
A tool for metrology and process control with sub-nanometer resolution based on SPM with very high throughput and many measurement possibilities, including surface topography and mechanical/chemical characterizations.

COMPETITIVE ADVANTAGE

Flexible, high throughput measurement platform capable of handling many different types of substrates.

APPLICATION AREAS

- Automated defect review (material characterization)
- Roughness measurement



- Patterned resist wafer
- Patterned wafers after etch
- Mask metrology
- Sub-surface defects & features
- DSA metrology

PROVEN SPECIFICATIONS:

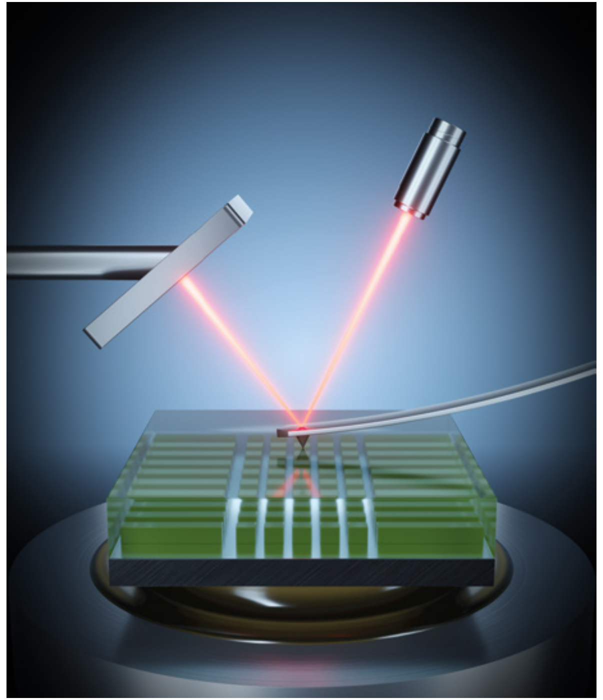
- Resolution x,y 5nm on 10x10 µm scan, 0,5nm on 1x1µm scan, z 0,5nm
- Drift 12nm/frame
- Scanning speed up to 13 lines/s
- Scan 450, 300, 100 mm wafer
- Each site circa 10 × 10 µm
- 4 sites in parallel

TARGET SPECIFICATIONS

- Resolution, z 0,1nm
- 40 sites in parallel
- Each site circa 20 × 20 µm
- Throughput based upon measurements requirements.
- Positioning accuracy: 200 nm

SUBSURFACE ULTRASONIC RESONANCE FORCE MICROSCOPY

The technology enables to measure and image features buried in compliant and non-compliant matrices and opaque layers at depths of several micrometers with nanometer resolution. These features can be both the desired features as well as unwanted defects like voids. In addition to that, the technique has the capability to perform compositional analysis. Properties such as elasticity and viscoelasticity at nanoscale can be extracted.



COMPETITIVE ADVANTAGE:

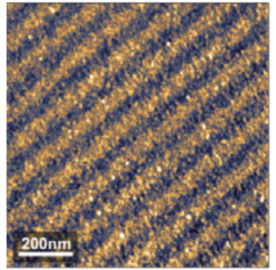
- Imaging of features deeply buried under multiple (opaque) layers
- Nanometer contrast/resolution
- Non-destructive
- 3D capability
- Chemical, physical contrast

APPLICATION AREAS:

- Nano-electronics industry;
  - To perform various non-destructive 3D, on feature and on-cell metrology for next generation of devices and nodes
  - To perform compositional analysis on layers and features below the surface
  - To assess mechanical and chemical properties of sub surface features and defects.
- Bio-nano applications;
  - Nano-imaging of internal cell structures, organs or other bio part with the goal to e.g. monitor disease evolution and drug efficacy.
  - seeing inside bio samples, such as living cells, organs or other bio particles. It can reveal the internal substructure of the cell, including the nucleus. These capability will have a broad impact in cellular biology, nano-medicine, toxicology and environmental studies.

PROVEN SPECIFICATIONS:

- Subsurface image of 50 nm nano-wires under stiff matrix of Silicon Nitride
- Subsurface image of 100-400 nm structures under 400 nm resist capping layer
- Subsurface image of 1800 nm structures under > 1.6 micron capping layer



Sub surface image of 50 nm nano-wires

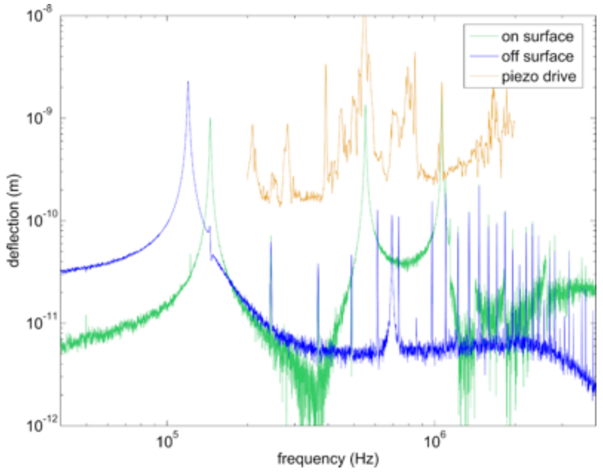
- Subsurface image of structures under various opaque layers

TARGET SPECIFICATIONS:

- Sub-100 nm hard structures buried under hard cover, with nanometer resolution,
- Quantitative analysis of physical properties

SUBSURFACE SCANNING PROBE MICROSCOPY USING ELECTROSTATIC ACTUATED CANTILEVER

Conventional top actuation Subsurface Scanning Probe Microscopy (SSPM) techniques utilize piezo driven actuators which impose significant thermal and mechanical noise to the frequency spectrum making quantitative subsurface measurements difficult or even impossible. Electrostatically driven cantilevers designed with a membrane tip which can be driven electrically dramatically reduce the induced noise and enables quantitative measurement of sub surface nanostructures.



COMPETITIVE ADVANTAGE:

- Very clean frequency spectrum enabling quantitative SSPM measurements
- Enables Frequency Modulation SSPM
- Top actuation removing the need for wafer stage modification
- High resolution and Signal to Noise Ratio

APPLICATION AREAS:

- Perform various non-destructive 3D metrology for next generation devices and nodes
- In-situ overlay measurement and device inspection
- Compositional analysis on layers and features below the surface
- To assess mechanical and chemical properties of sub surface features

PROVEN SPECIFICATIONS:

- no spurious peaks in excitation spectrum DC – 4MHz
- maximum obtainable excitation amplitude ~20 nm
- maximum excitation frequency ~30MHz

TARGET SPECIFICATIONS:

- maximum obtainable excitation amplitude > 5 nm
- maximum excitation frequency > 30MHz
- 1st cantilever contact resonance <300kHz
- cantilever stiffness range 5 N/m – 100 N/m

NANO-MECHANICAL FORCES IN SCANNING PROBE MICROSCOPIES

New probes, operation methods, control and signal processing techniques to enhanced functionality and performance of AFM via online estimation and active manipulation of the tip-sample interactions.

COMPLETIVE ADVANTAGE:

- High speed non-destructive imaging with nanometre resolution
- High precision mapping and recognition of material properties of samples
- Patterning with nanometre resolution

APPLICATION AREAS:

- Imaging of soft samples such as self-assembled monolayers and biological samples
- Inspection, metrology and process control
- Mask-less nano-patterning, photomask modification and repair

PATENT:

1 Method of operating Atomic Force Microscope with wide band probes, direct force controlled mode
2 Method of simultaneous nano-patterning and imaging with Atomic Force Microscope

PROVEN SPECIFICATIONS:

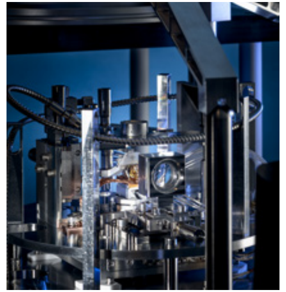
- Non-destructive imaging and increasing lifetime of the tip via reduction of forces
- Increased sensitivity and online material properties mapping
- Simultaneous imaging and nano-machining by increasing the forces in a controlled manner
- Real-time Estimation of the tip-sample forces
- Predicting the forces in transient situations

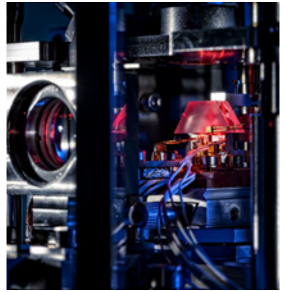
TARGET SPECIFICATIONS:

- High speed imaging via advanced control design to meet the measurement requirements
- Extended throughput by parallel operation of multiple probes on the same chip

MEASURING DISTANCES WITH NEARFIELD HEAT RADIATION

Precise and accurate distance measurement at the micro- and nanoscale at the point-of-interest is a key capability for enabling high throughput imaging using near-field optical systems. This capability can be provided be accurately measuring the heat-flux between a probe and the sample. As a separate technology such a system can be used as a fully contactless scanning probe microscope that provides topography and local heat fluxes.





COMPETITIVE ADVANTAGE

- Fully non-contact and non-invasive
- Sub-nanometer resolution
- Less substrate dependent compared to optical or electrical techniques
- Offers measurement at the point-of-interest (very close to the lens)

APPLICATION AREAS

- High resolution positioning sensor
- Near-field optical systems
- Scanning probe microscopy
- Semiconductor metrology and inspection
- Nano-patterning

TARGET SPECIFICATIONS

- 20 pW precision and 2 nW uncertainty in heat flux measurements
- Sub-nanometer precision in distance measurement at distances below 100 nm
- Fully contactless imaging

MEASURING THE TIP-SAMPLE INTERACTION FORCES IN TAPPING MODE AFM

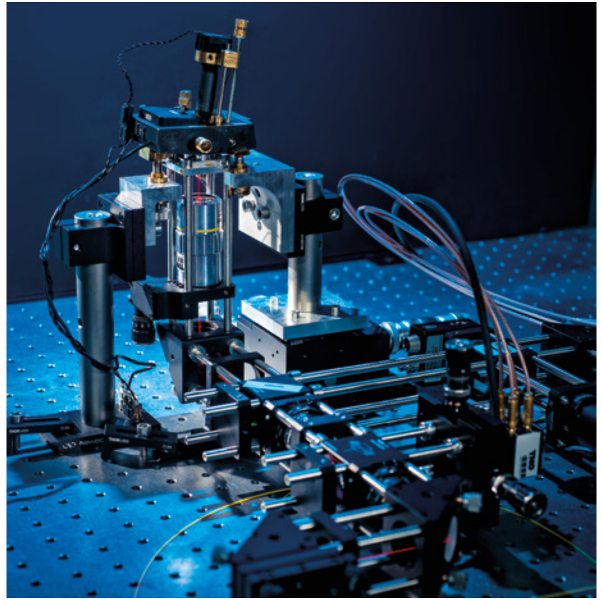
A new concept for quantitative measurement of the tip sample interaction forces in tapping mode atomic force microscopy using a high speed and high sensitivity force sensor, simulating the sample surface at the same time.

COMPLETIVE ADVANTAGE:

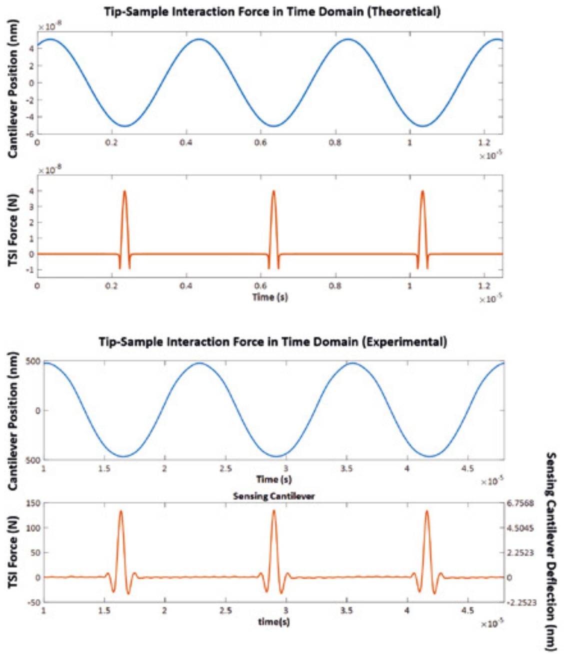
- Quantitative measurement of the tip-sample interaction forces with high sensitivity and resolution.
- Compatible with all types of conventional and special design cantilevers used for AFM imaging and all types of operation modes.
- Enabling experimental simulation of different surface scenarios and the change in tip-sample interaction forces.

APPLICATION AREAS:

- Increase the tip lifetime, the imaging accuracy with AFM
- Inspection, metrology, and process control



AFM setup for tip-Sample Interaction measurements.



Tip-Sample Interaction Force in Time Domain (Theoretical)

PATENTS:

- Method of quantitative measurement of the tip-sample interaction forces
- Method of simultaneous nano-patterning and imaging with Atomic Force Microscope

PROVEN SPECIFICATIONS:

- Low force and displacement measurement 8.8 pN/sqrt(Hz), 400 nm/sqrt(Hz)
- Excellent match with the theory
- Calibration of the tip-sample forces before imaging desired surface

TARGET SPECIFICATIONS:

- Increase the accuracy of the measured tip-sample interaction forces
- Simplify the measurement process for commercial AFM systems

CHARACTERIZING ELECTRON BEAM INDUCED DAMAGE IN METROLOGY AND INSPECTION OF ADVANCE DEVICES

The semiconductor manufacturing technologies require usage of low dielectric (low-k) materials together with novel metrology tools. The electron beam (e-beam) has emerged as a complementary metrology and inspection tool. However, the e-beam can cause damages to the materials under inspection due to its relatively high energy. Here, we present scanning probe microscopy techniques with the capability of measuring the e-beam induced damages on various materials. These techniques can be considered as a complementary approach to e-beam to ensure minimizing damage to the features

COMPLETIVE ADVANTAGE:

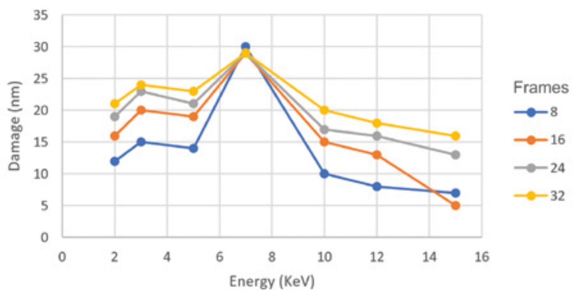
- scanning probe microscopy technique with the capability of measuring the e-beam induced damages on various materials.
- a complementary approach to e-beam to ensure minimizing damage to the features
- detect visco-elasticity change of materials caused by e-beam.

APPLICATION AREAS:

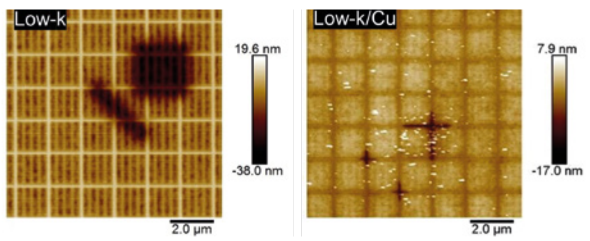
The e-beam induced damages is investigated on two sets of samples (300 mm wafers):

1 Patterned low-k material on Si wafer.
2 Patterned low-k material on Si wafer filled with copper (Cu).

Systematic damage is induced by scanning the e-beam over square areas of the size 2×2 µm2. The exposure energy and the dose (number of frames) are varied at each location.



e-beam damage on low-k sample



Measured e-beam damage formation

EBEAM DAMAGE LOW-K SAMPLE

- the e-beam damage is uniform.
- At fixed energy, damage increases linearly with dose.
- At fixed dose, damage is higher at certain energy windows (7kV)

EBEAM DAMAGE LOW-K/CU SAMPLE

- Overall damage is much less than in the low-k sample.
- The e-beam damage is more pronounced on the low-k material, away from the copper. Detectable damage on the low-k/Cu lines only at the e-beam energy of 7kV
- Overall height drop we assign to the damage of the underlying low-k material beneath the low-k/Cu lines.

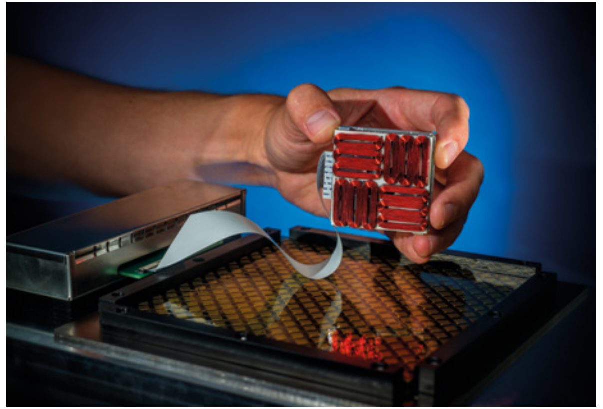
TNO RESONANCE-SHIFT METHOD

- The e-beam exposure can slightly modify the visco-elastic properties of the materials on the sample.
- This visco-elasticity change can be detected by our technique as it modifies the resonance characteristics of the probe.

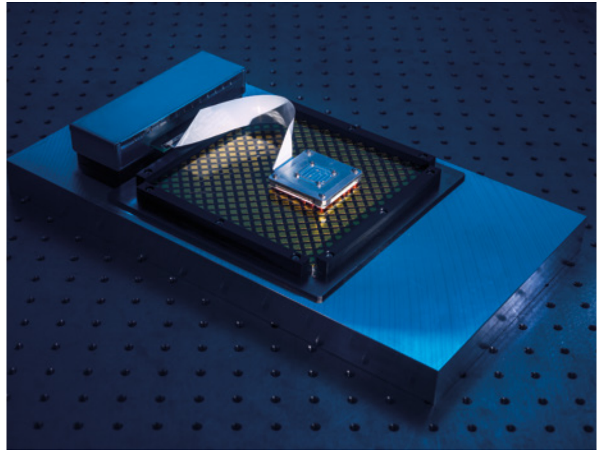
NANO-PRECISION MULTI-AGENT MAGLEV POSITIONING PLATFORM

Positioning platform is the development of flexible positioning systems for different types of nano imaging and manufacturing tools. The small footprint enables flexible parallelization and high throughput by using multiple independently positioned carriers. The carriers are based on magnetic levitation which enables combination of large stroke and fine resolution with little disturbances from the environment. A first version is being realized to verify feasibility and critical technologies. A matching metrology system for measuring the multiple carriers' positions has already been identified as critical and is being investigated separately.

The envisioned positioning Platform is a flexible, wireless, multi-tool positioning platform which can position tools on a wafer or a mask independently.



Realized 50x50mm carrier with moving coils on an Hallbach array of magnets.



Main purpose is achieving a high throughput and parallelized 3D metrology, nano-imaging and manufacturing. The small footprint enables multiple tools per wafer or mask.

APPLICATION AREAS:

- Positioning of a scanning probe, optical or manufacturing tools
- Wafer and mask Inspection or review
- Lithographic processing and repair tools.
- Rapid manufacturing tools with increased speed (by parallelization).

PROVEN SPECIFICATIONS:

A demonstrator has been build and tested and currently the levitation and coarse positioning control are being implemented.

TARGET SPECIFICATIONS

- Size: first version 50x50x50 mm, going down to 10x10x10 mm within a few years
- Carrier total mass: ~200g (for 50x50x50 mm carrier size)
- Horizontal scanning range: 300 mm wafers and larger.
- Vertical scanning range: +/-100 um
- Absolute positioning accuracy: <10 nm (future target)
- Scanning resolution: 0.1 nm (future target)
- Acceleration: >10 m/s2
- Target cost per carrier platform (excluding sensor tool): <10 kEuro

HIGH BANDWIDTH, PICOMETER RESOLUTION NANOPOSITIONING STAGE FOR METROLOGY APPLICATIONS

A nano-scale controlled MEMS nanopositioning stage for high-throughput applications in nearfield positioning of nearfield optical elements or SPM probes. The MEMS stage uses parallel sensing by means of capacitive actuation and capacitive sensing for feedback control.

COMPETITIVE ADVANTAGE

High-speed (500 kHz resonance frequency) , accurate positioning of sensors for nearfield sensing. The high Eigen frequency will enable a high control bandwidth that will allow high scan speeds while tracking surface features.

APPLICATION AREAS:

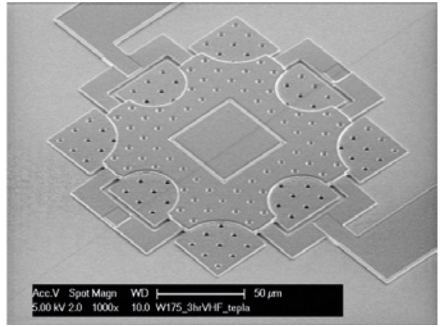
- Optical nearfield microscopes
- Scanning probe positioning

PROVEN SPECIFICATIONS

- 500 kHz Eigen frequency

TARGET SPECIFICATIONS:

- 500 kHz Eigen frequency
- 150 nm range-of-motion
- 1 pm positioning resolution



SEM image of a finished MEMS device

3D PROFILE MEASUREMENT OF HIGH ASPECT RATIO NANOSTRUCTURES

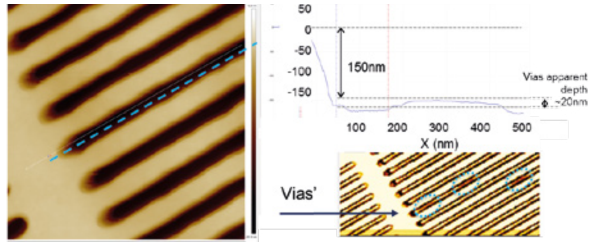
Measuring the full profile of the 3D structures such as FINFET and Gate all around Nanowires is one of the current nanometrology challenges. A proof of Principle setup tis being developed to measure the full profile of High Aspect Ratio 3D structures by force controlled profiling.

COMPETITIVE ADVANTAGE

- Full profile of High Aspect Ratio structures with sub-nanometer resolution
- High bandwidth controlled tip sample interaction to follow structures without damage or jittering.
- Extraction of CD, SWA, SWR, LER

APPLICATION AREA'S

- Critical dimensions (CD) Length, height with and profile
- 3D shape
- Side Wall Angle (SWA)
- Side Wall Roughness (SWR)
- Line Edge Roughness (LER)



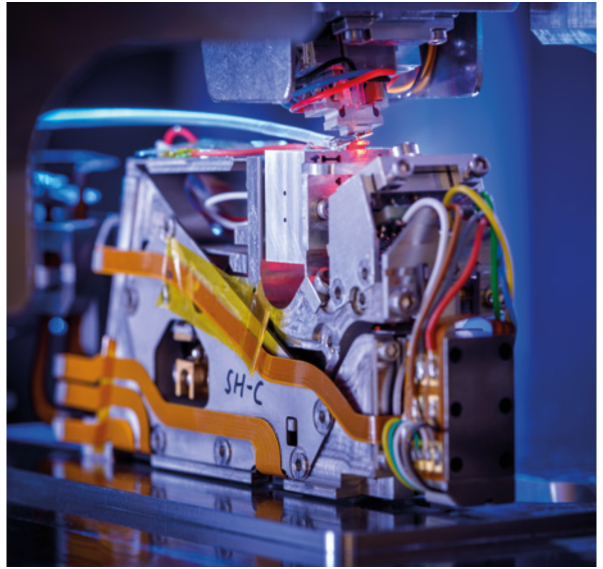
Imaged in low-k material 30-50nm width trenches, depth of trench 150nm deep. Aspect ratio 1:4 or 1:5. Via's at ~170 nm depth from the surface can been seen.

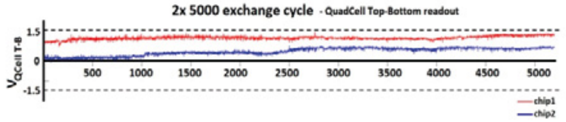
TARGET SPECIFICATIONS.

- 3D measurement of FinFET and the oxide recessed etch
- Gate all around nanowires
- Contact holes

AUTOMATED CANTILEVER EXCHANGE AND OPTICAL ALIGNMENT FOR HIGH-THROUGHPUT, PARALLEL ATOMIC FORCE MICROSCOPY

An automated cantilever exchange and optical alignment instrument is developed. Experimental proof of principle by exchanging various types of AFM cantilevers in 6 seconds with an accuracy better than 2 um is demonstrated. The exchange and alignment unit is miniaturized to allow for integration in a parallel AFM. The reliability of the demonstrator has also been evaluated. Ten thousand continuous exchange and alignment cycles were performed without failure. The automated exchange and alignment of the AFM cantilever overcome a large hurdle toward bringing AFM into high-volume manufacturing and industrial applications





The cantilever align reliability shown with two series of 5000 tip exchange and align cycles

COMPETITIVE ADVANTAGE

The cantilever exchange functionality, performance and reliability were successfully demonstrated in a AFM. This automated, miniaturized cantilever exchange and alignment can be integrated in a parallel AFM. The cantilever exchange time is 6 seconds, and the alignment accuracy is better than 2 µm. The accuracy and reliability of the cantilever placement were demonstrated with two successful runs of 5,000 cycles without human interruption.
The imaging performance was verified after 1 and 150 automatic cantilever exchanges.

APPLICATION AREA'S

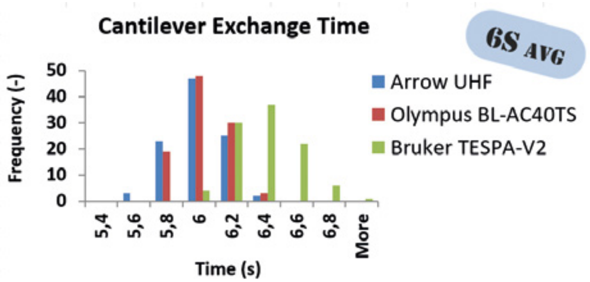
– High Throughput parallel AFM system of TNO
– Inline metrology in semiconductor manufacturing processes

PROVEN SPECS

– Exchange time is 6 ±0.8s
– Align reliability, 10,000 cycles image
– Cantilever Placement, width cantilever ±0,25µm, length cantilever ±2,3µm,
– Exchanged and aligned tips, Arrow UHF, Olympus BL-AC41, Bruker Tespa-V2

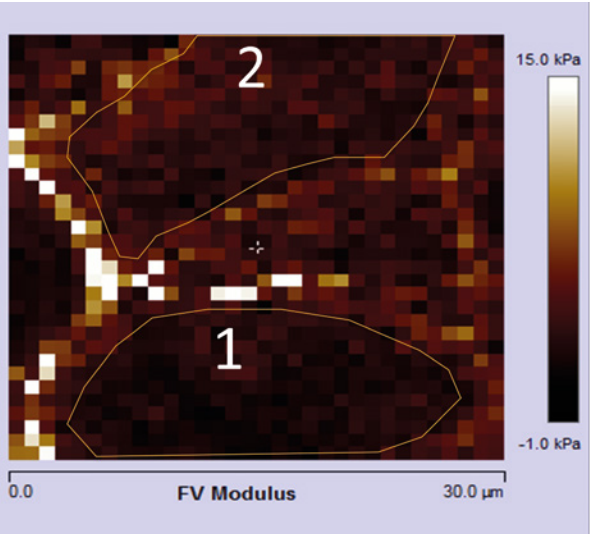
TARGET SPECIFICATIONS.

– Integrate in High Thoughput Parallel AFM



BIO-NANOMEDICAL INSTRUMENTS

TNO is exploring the added value of the nano-mechanical biosensors for monitoring cells, epithelium layers and organoids. Nanoscale in-line measurement and monitoring of mechanical properties (mass and stiffness) of cell layers, individual cells and organelles of cells subject to external stimuli reveal a high contrast between normal cells and cells in stress. This novel non-destructive imaging modality enables early identification, in vitro disease mechanisms studies and enhancement of drug efficacy studies.



Young's Modulus diagram of measured area with cells

COMPETITIVE ADVANTAGE:

- Complimentary to existing imaging modalities.
- Reliable identification and monitoring due to high accuracy and nano-scale resolution.
- Cell-related information due to nano-imaging in the cells.
- Effective and early detection of nano-mechanical changes of cells and viruses.
- More enhanced efficacy study due to highly sensitive in-line measurement of cell response.

APPLICATION AREAS:

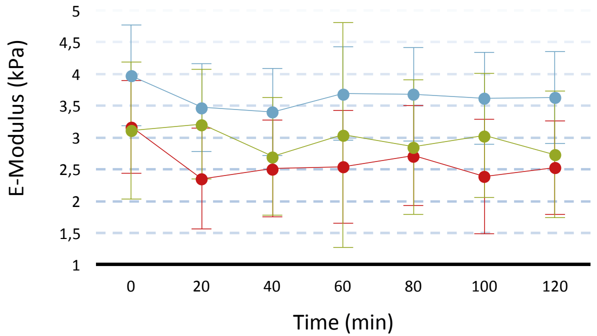
- Research tool.
- Automated tissue screening.
- Pre-clinical in-vitro pharmacodynamics and pharmacokinetics studies.

PROVEN SPECIFICATIONS:

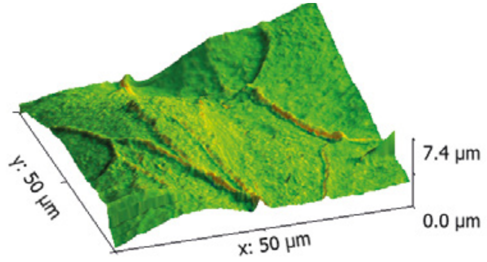
- Young's modulus measurement reproducibility; < 1kPa.
- No degradation in cells during measurements for at least two hours.

TARGET SPECIFICATIONS:

- In-vitro nano-mechanical response monitoring of cells, epithelium layers and organoids in stress.
- Monitoring different organelles of cells.
- Correlation of the nano-mechanical properties to the bio-chemical processes.
- High degree of automation.
- Monitoring at production rate with easy-to-use setup.



Change in Young's Modulus over time for the recorded area (BLUE), cell #1 (RED), cell #2 (GREEN).



Surface topology of monolayer of cells

VIRUSCAN - IDENTIFICATION AND CHARACTERIZATION OF VIRUSES FROM THEIR NANO-MECHANICAL PROPERTIES

The nano-mechanical physical properties of viruses are highly conserved during the virus evolution. Obtaining the viral mass by mass-spectroscopy is well known. VIRUSCAN aims to detect individual viruses of human samples and identify the viruses from their mass and stiffness. The nano-mechanical properties are determined by measuring the resonance frequency shift of nano-disk resonators due to soft-landing of individual virions. Addressing the stiffness of viruses opens a new route to assess the infectiveness of viral traces in human samples, which is a difficult with present technologies.

COMPETITIVE ADVANTAGE:

- Integrated approach for biophysical detection and identification of viruses.
- Identification and characterization based on mass and stiffness.
- Use of low-cost microfluidics and nanomechanical devices for high resolution mass-stiffness measurements.
- No need for a-priori knowledge and thus primers enabling rapid identification of mutated viruses.
- Ability to extract maturation phase of the viruses.

APPLICATION AREAS:

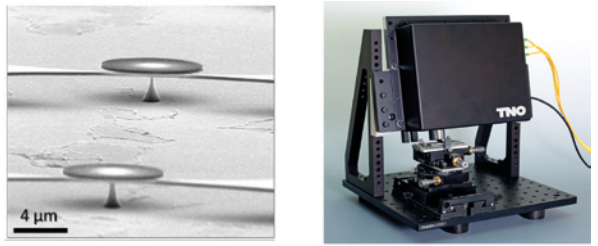
- Personalized treatment of patients
- Reducing the use of antibiotics and thus preventing antibiotic resistance
- Direct and accurate on-site response to emergency situations
- Drug efficacy analysis
- Reduced cost per analysis allows screening of a wide range of pathogens

PROVEN SPECIFICATIONS:

- First specifications expected in 2018. Operational TRL4 demonstrator expected in 2021.

TARGET SPECIFICATIONS:

- Measured mass between 106 and 1011 DA at 1% resolution.
- Measured stiffness between .02 and 3 N/m at 1% resolution.
- Virus concentrations of between 101 and 106 virions/mL.
- Sample processing time in the order of 30 minutes per sample of 1 mL.
- Operational in BSL-1 to BSL-4 lab.



Nanomechanical disk resonator developed by UPD (left) and TNO-FRESCO setup (right)

ViruScan

TNO innovation for life

FasmaTECH

SaludMadrid

leti cea tech

rijksuniversiteit groningen

HPI

Instituto de Micro y Nanotecnología IMN-CNM

VIRUSCAN partners

CONTACT

TNO
Hamed Sadghian
E hamed.sadeghianmarnani@tno.nl

TNO.NL

17-9058 oktober 2017