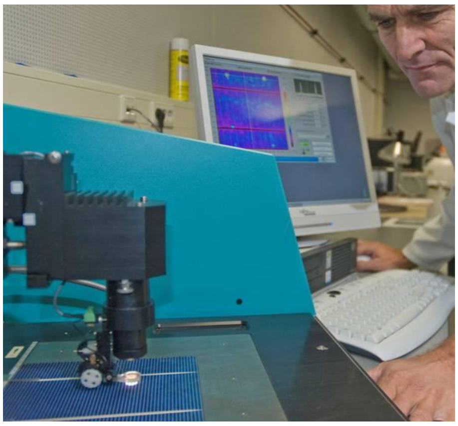
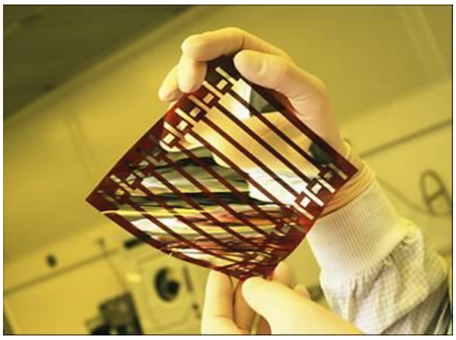
geZONd

GEzamenlijke faciliteit voor ZONnepaneelanalyse en Duurzaamheidstesten

Contract ID: PiD-ZON 09-01

New test and characterization methods for PV modules and cells





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Abstract

This report describes the results of project geZONd (*shared facility for solar module analysis and reliability testing*), set up by Philips, ECN, Holst, Solland, OM&T, and Holland Innovative. The partners have shared most of their testing and analysis equipment for PV modules and cells, and together developed new or improved methods (including the necessary application know-how). This enables faster and more efficient innovation projects for each partner, and via commercial exploitation for other interested parties.

The project has concentrated on five failure modes: corrosion, delamination, moisture ingress, UV irradiation, and mechanical bending. Test samples represented all main PV technologies: wafer-based PV and rigid and flexible thin-film PV. Breakthroughs are in very early detection of corrosion, in quantitative characterization of adhesion, in-situ detection of humidity and oxygen inside modules, and ultra-fast screening of materials on UV stability.

Keywords

Photo-voltaic module, photo-voltaic cell, PV degradation, reliability testing, non-destructive analysis, failure analysis, encapsulant

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1 Introduction

This report describes the results of project geZONd, acronym for '**ge**zamenlijke faciliteit voor **zon**nepaneel-analyse en **d**uurzaamheidstesten' (Dutch for *shared facility for solar module analysis and reliability testing*). This project was set up in May 2009 by six partners, all partly or completely based in the South-East of the Netherlands:

- Philips Electronics Nederland B.V.
- ECN (Energy Research Centre of the Netherlands)
- Holst Centre
- Solland Solar Cells B.V.
- OM&T B.V. (part of Moser Baer India Ltd.)
- Holland Innovative B.V.

The main goal of the project is to create a shared facility (including shared expertise and application know-how) of new or improved testing and analysis equipment for PV modules and cells. As the necessary infrastructure is often very expensive and hardly ever used full-time by one individual party, this sharing results in significant cost savings. Moreover, sharing knowledge of advanced testing and analysis methods and protocols enables faster and more efficient innovation. Also advanced modeling of degradation, failure and lifetime of PV modules is an aim of the project. The facilities and expertise are used by the partners themselves and offered to other parties by commercial exploitation. Thus, the project creates a competitive advantage for the PV industry of the Netherlands, and more specifically the South-East region of the Netherlands, over the rest of the world.

The project was sponsored by the Ministry of Economic Affairs, in the program *Pieken in de Delta*, "Programmalijn Open Innovatie, actielijn 4.3 Stimuleren van samenwerking bij de ontwikkeling van facility sharing". Co-sponsors are the Province of Noord-Brabant, the Province of Limburg and the SRE (Samenwerkingsverband Regio Eindhoven). The project was sponsored from 1-10-2009 till 31-3-2012 (2½ years).

2 Approach

In the original work plan, four work packages (WP) were distinguished:

1. Research and specification
2. Testing and analysis
3. Modeling and validation
4. Project management

The first work package has two main goals: (i) finding out and describing the state of the art and (ii) specifying the equipment, methods and models that will be investigated and developed within the rest of the project.

The second and third work packages are the core of the project. Here, new equipment is designed and built, test modules are produced, stressed and analyzed and test data is modeled.

The first work package has resulted in two reports[2]:

- D1.1: **Report on failure mechanisms in solar modules**
- D1.2: **Selection of failure modes, test modules and test and characterization methods**

Report D1.1 is an extensive description and discussion of the literature on failure of PV modules. It has proven an important reference work to all partners. The main conclusions are:

- For crystalline silicon modules, the most common degradation mechanisms observed in the field are interconnect failure (either corrosion or fatigue) and delamination. Both corrosion and delamination are heavily accelerated in the presence of moisture.
- For rigid or flexible thin film silicon modules the most critical stress factors are moisture ingress, UV irradiation and bending causing encapsulant/packaging degradation, contact corrosion and insulation failure.

[2] Both reports are available upon request with the corresponding author, see title page.

- For organic modules, the chemical and physical stability of the photoactive and adjacent layers and the encapsulant properties are critical to the lifetime. These are heavily affected by oxygen, moisture, increased temperature and UV.

Report D1.2 describes the selection and specification of the materials and methods to be investigated in the rest of the project. It was decided to concentrate on five stress factors or failure modes:

1. Corrosion
2. Delamination
3. Moisture ingress
4. UV irradiation
5. Mechanical bending

The work of WP2 and WP3 has been organized in line with the five topics. Five development teams were formed, one for each topic, concentrating on the most important test and analysis issues for their topic. This deviates from the original work plan, where the work was structured according to the type of activity (e.g. test design, equipment construction, materials analysis, modeling). However, there is no deviation from the content of the original work plan: all items are still addressed, but differently distributed. Regular adjustment of plans and exchange of results between the teams have been organized to avoid undesirable overlap or important gaps in the total body of work.

It was also decided to put more emphasis on testing and analysis (originally WP2), less on product modeling (originally WP3). The arguments for this decision are budget limitations and confidentiality issues (failure and lifetime modeling involves more sensitive data than incidental test & analysis). Modeling of test data (e.g. determining of acceleration factors, fitting impedance spectra & IV curves) has remained an essential part of the project.

Table 2.1 shows for each development team the partners involved, the material system tested, and the main test and characterization methods applied. The overall project management was with Philips.

Table 2.1: Development teams, with partners involved (leading partner in bold) and main methods applied.

Development team	Partners	PV technology	Test method(s)	Analysis method(s)
Corrosion	**ECN**, Solland, Philips	Wafer-based	damp-heat + biased	Differential resistance, noise, microscopy, chemical analysis
Delamination	**Solland**, ECN, Philips	Wafer-based	damp-heat, PCT, thermal shock	acoustic, DLIT, peel, core-shear, chemical analysis
Moisture ingress	**ECN**, Holst, Holland Innovative, Philips	Flexible thin-film	damp-heat, condensed water	in-situ EIS, IV, chemical analysis
UV	**OM&T**, Philips, Holst, ECN	All: packaging materials	UV + damp-heat	optical, chemical
Mechanical bending	**Holst**, Philips, ECN	OPV: barrier materials	mechanical, gas permeation, dye colour change	optical microscopy and spectroscopy, gravimetry

The next five chapters describe the results obtained within the five development teams.

3 Corrosion

Corrosion is the main cause of power loss in crystalline PV modules. For H-cell modules, the corrosion occurs between cell metallisation and solder on tabs. For back contact modules, galvanic corrosion occurs between Ag and Al. ECN has sometimes observed corrosion after damp heat tests. In this case, the Al/Ag overlay region of a base contact is corroded. Since this corrosion mechanism is significantly different from the corrosion observed in H-pattern modules (corrosion between tab and solder), the understanding of this process is still low. Several issues are currently unknown:

- Is it galvanic corrosion?
- What is the corrosion speed?
- Is there an influence of the encapsulant (e.g. through local pH or local amount of water)?
- Is there an interaction with other components?
- Is there an influence of the morphology, due to the Ag or Al paste type?

The development team *Corrosion* has investigated new test and analysis methods for electrochemical reactions in the electrodes and interconnects, particularly the detection of corrosion in-situ in a climatic chamber, such that the process can be followed and failure rates can be determined. Multi-crystalline PV modules have been used as test objects. Electrical measurements (differential resistance) of special test structures inside the PV modules during the climate test have been implemented. An electrochemical noise (EcN) measurement has been developed to test corrosion rates much faster than typical climate chamber tests (see Figure 3.1). For analysis, electrochemical impedance spectroscopy (EIS) has been used, complemented with local chemical and morphological analysis, in particular (planar or cross-section) SEM-EDX.

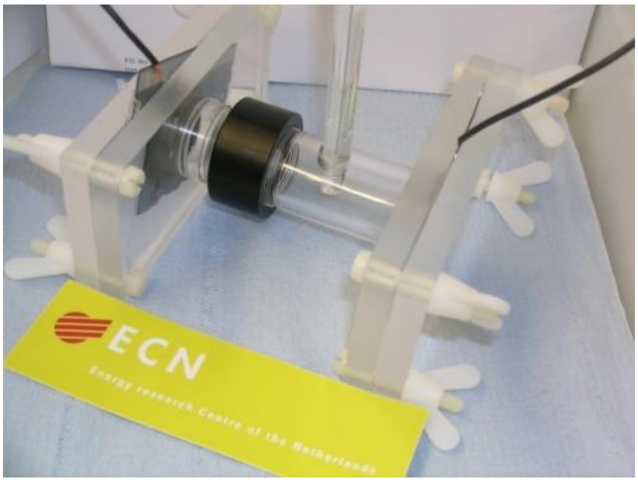

Figure 3.1: Photographs of the electrochemical noise set-up. In the centre of the electrolyte container, a reference electrode is placed. The right hand picture shows the piece of an MWT solar cell clamped between two polymer blocks.

We conclude that EcN is a very useful tool for corrosion prediction. Therefore, it is already applied within *ECN – Solar energy* as a predictive tool. We foresee possibilities for EcN in the solar industry, both for testing new batches of metal pastes and encapsulant in a production facility, and for pre-selecting new material combinations in an R&D environment. The EcN setup is sensitive to the lay-out of the tested samples and the microstructure of the materials involved. Choosing the right electrolyte allows fast testing (within a day). ECN is working on the valorisation of these results.

More work is still needed to decide the applicability of the moisture sensor at present. The usefulness of a cheap, reliable moisture sensor which can be laminated in a PV panel is clear for lifetime testing in the field.

4 Adhesion and delamination

The development team *Adhesion and delamination* has focused on analysis methods for early or non-destructive detection of weak interfaces or beginning of delamination. Standard and deliberately weakened test modules of multi-crystalline Si have been exposed to standard climate tests (Damp Heat or DH) and to a pressure cooker test (PCT) to promote delamination. The analytical techniques applied to study the effects of the accelerated tests can be subdivided in two categories:

- **Non-destructive detection of actual delamination.** Here, Lock-in Thermography (LIT) and Scanning acoustic microscopy (SAM) have been used. The aim of these studies was to find and/or develop a technique that allows for a non-destructive, reliable, and preferably fast detection of delamination in cells and/or modules.
- **Destructive analysis quantifying the adhesion strength at the interfaces.** By monitoring a reduction of adhesion strength over lifetime, the degradation eventually leading to delamination can be detected and quantified prior to the delamination event itself. This may enable higher acceleration of lifetime testing. For the present study the well-established peel-test is compared to a technique that is new to solar research: the core-shear test.

Three sets of test samples have been produced and exposed to DH and PCT. PCT appeared to induce a failure mode different from loss of adhesion strength: degradation of the encapsulant, yielding bubble formation within the encapsulant layer. The PCT test is therefore considered not suitable for realistic lifetime testing. DH testing induced a significant reduction in adhesion strength, thereby allowing for characterization of this failure mode. No significant delamination was induced in the test samples.

Adhesion strength was tested using peel-testing and core-shear equipment built within this project (see Figure 4.1). For the present set of samples, peel strength measurements are difficult to interpret due to inherent limitations (elasticity, brittleness) of the foils. A complication of core-shear testing here is that samples often delaminate during (mechanical) coring, so that no quantitative shear measurement is possible. This was solved by developing a laser coring technique. We found that the adhesion strength of all laminates decreases with prolonged DH duration. Back contact modules often fail at one of the interfaces of the solder mask.

Figure 4.1: Left: overview image of the core/shear set-up. Right: detail of the torque-head.

Delamination (e.g. of back-sheet foil, or around contact holes) can non-destructively be characterized using LIT, SAM and Moire imaging. We have developed a special thermally modulated LIT technique, which allows thermography also when electrical addressing of the cell/module is not desired or possible (see Figure 4.2). SAM not only enables visualization of delamination, but also displays chemical degradation at the interface, thereby providing indications for possible changes in adhesion strength prior to actual delamination.

ToF-SIMS, SAM and IR studies on the interface with reduced adhesion strength showed that compositional changes can be detected at this interface. Although no in-depth study of the chemical mechanisms inducing loss in adhesion have been performed, our preliminary studies show that ToF-SIMS and IR can provide detailed insight into the underlying mechanism for loss of adhesion strength.

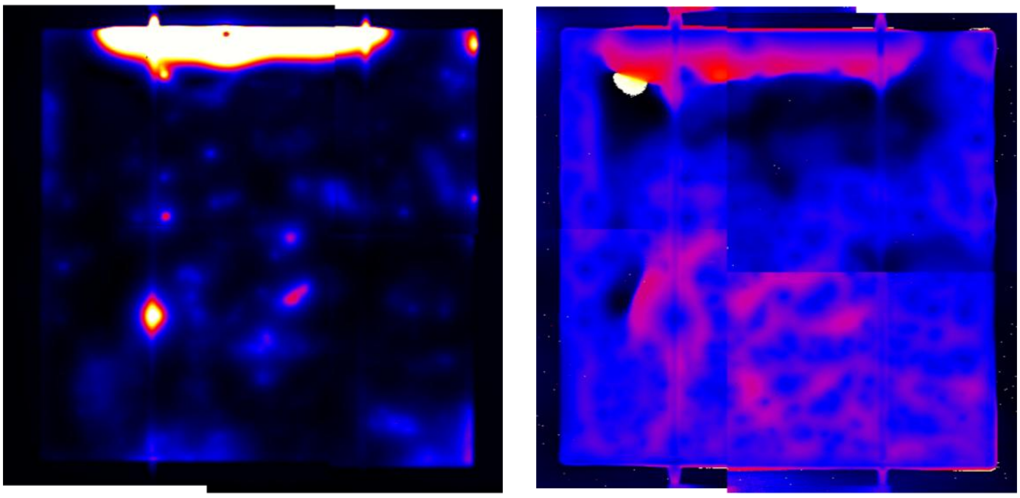

Figure 4.2: TM-LIT amplitude (left) and phase (right) images of cell A854, displaying delamination at one of the edges of the cell prior to DH testing. Because of this 0h failure, this cell was not used for further testing.

5 Moisture ingress

In this team, accelerated test methods were developed for the degradation of PV modules by ingress of water. In particular, the team looked at climate chambers that produce condensed water and compared with standard climate chamber testing. The modules under study were commercially available flexible PV. In parallel, methods for electrical (electrochemical impedance spectroscopy (EIS)) and chemical (e.g. optical spectroscopy) analysis of the materials in a humid environment were (further) developed. Ideally, these methods detect material alterations much earlier and follow the alteration during moisture ingress.

Part of the work within the package humidity ingress involves an investigation of the feasibility of controlled condensation exposure for reliability determination of modules and determination of its added value in comparison with current exposure methods. Currently, new modules are usually exposed according to the IEC 61215 (IEC, 2005), which includes a damp-heat test, a humidity freeze test, a hail impact test, and a thermal cycling test. One could however argue that the sensitivity of the modules to water condensation is not properly covered by these tests, while condensation is a stressor during normal outdoor use.

The main differences between condensation exposure and other tests are the presence and the distribution of the condensed water on the surface of the module. With most other methods of exposure no (liquid) water comes in contact with the surface at all. If water is sprayed on the module surface, the surface will of course be covered, but filling of any pinholes with water is unlikely. Condensation, on the other hand, is most probable to occur at irregularities in the surface. (Umur & Griffith, 1963) As a result, any pinholes in the surface are likely to be filled with water. Therefore, exposure to condensation may be more detrimental to a module than exposure to humidity alone or to (random) water spray. The aim of this part of the project is thus to investigate to which extent water condensation is indeed a more effective stressor than the (standard) humidity exposure tests.

Accelerated ingress of water into thin film PV modules has been achieved by means of moisture condensation on commercially available devices tested. Powerfilm and Konarka Power plastic have shown to be susceptible at various levels to increased moisture stress driven by condensation on the samples (see Figure 5.1 and Figure 5.2). Standard Powerfilm is very sensitive to condensation conditions, ultimately resulting in complete disintegration of the module. The “weather pro” Powerfilm, with more robust encapsulation, degrades much less. For Konarka power plastic a strong performance decrease is observed without any visual changes.

Condensation conditions obviously accelerate the ageing of the samples tested compared to just damp heat testing at the same temperature (investigated in a T range from 62-72 °C) but also compared to standard damp heat testing at higher temperature (85 °C)! Generally spoken this makes ageing under condensation conditions a very suitable method to assess susceptibility of PV modules towards moisture ingress in a short period of testing. Specifically for the type of thin film modules tested it is important that this is also feasible without temperature overstressing, which is inherent to standard damp heat testing for this type of modules.

To further confirm the accelerated degradation due to condensation conditions, with respect to ‘standard’ 85% RH humidity conditions, it is also advised to test at least 8-10 solar modules per test, to find statistically significant differences, not obscured by differences of the solar modules resulting from production process variations.

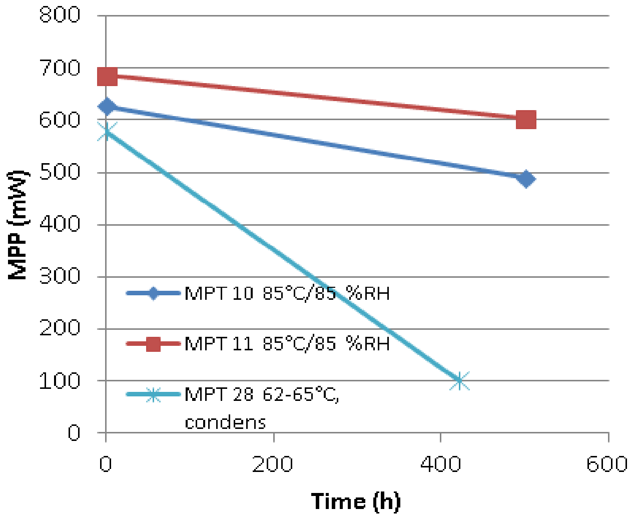

Figure 5.1: Change of power output for condensation conditions during 422 h at T= 62-65°C, RH=76-89% compared to a 500 h damp heat test (85°C/85% RH) for several shiny MPT6-150 samples.

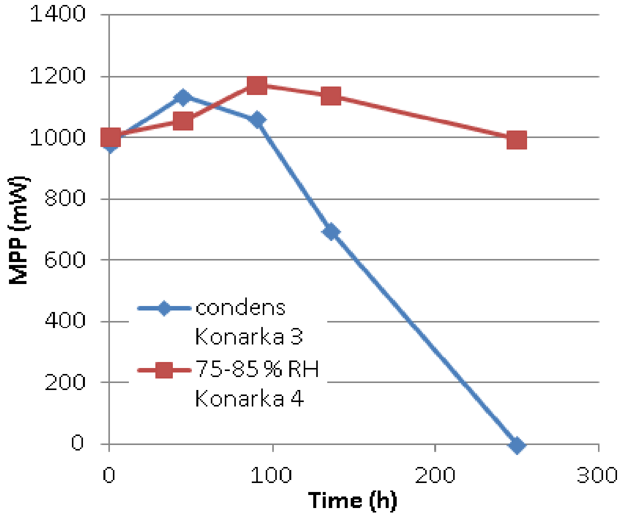

Figure 5.2: Change of power output for humid and condensation conditions compared for two Konarka samples during 250 h at T= 68-72°C/ RH=75-85 %.

Electrochemical impedance spectroscopy has proven to be a valuable and sensitive tool for in-situ monitoring of samples under test, since changes observed in impedance spectra reflect changes in device performance as can be measured by IV measurements. The strength of the technique is in its sensitivity (gage R&R for Rseries is excellent for MPT and P samples), but mainly in the early detection of (small) changes, inherent to the "in-situ" option which is impossible using IV measurements. Moreover EIS is generally applied to make in depth electrochemical analyses of devices and can be a strong tool to reveal failure mechanisms. This requires substantially more efforts in modeling and understanding the physical meaning of equivalent circuits that can be derived from EIS measurements, specifically for thin film PV modules.

Raman spectroscopy could also be used to investigate degradation, at least for the MPT samples investigated, making use of peak area and peak height for Si and PE layers, and of peak height for PET layers. However, this technique cannot be used in situ during exposures at present. Additionally further work is required to improve the measurement setup and to optimize the fitting program, before this technique could be applied in a more commercial way. Thus EIS measurement remains the most promising technique for in-situ early detection of solar module degradation.

6 UV irradiation

In the design-phase of new solar-cell concepts it would be nice to know the stability of the different materials in advance. Stability under light exposure is essential for most solar cell components. Existing test methods are not very helpful due to two shortages.

1. They usually aim at the qualification of complete panels. This leads to large test set-ups with relatively low intensities and acceleration factors, but very high power-consumption and prices.
2. The IEC-qualification standards (61215, 61646 and 61730-2) are relatively mild. They correspond with 71 or 181 days outdoors.

To get realistic information about the performance of materials and assemblies after 10 or 30 years outdoors we will need other tests and extrapolations.

This team tries to find methods to get information about the light-stability of new materials much faster and cheaper, using much smaller sample sizes and higher light intensity (but controlled sample-surface temperature). Because generally most damage is caused by the UV-part in the spectrum, we have restricted our testing to the UV-part. This has the large advantage that unrealistic thermal heating of the sample is held off. We have allowed the use of several strong emission lines instead of requiring a sun-like spectral distribution to make the lightsource cheaper. Finally, the use of hypersensitive analysis methods could possibly also shorten the exposure times that are required.

We have built a special set-up for highly accelerated UV exposure while controlling the sample surface temperature inside a climate chamber (see Figure 6.1). We compared results with standard 1-sun UV exposure and tried to determine the acceleration factor. Samples used for the tests were encapsulant films on glass and polymer foils with or without SiN barrier. For characterization of the material changes, we use the following optical methods: (i) UV-Vis: Wavelength Resolved Optical Transmission through the sample, (ii) FTIR: Attenuated Total Reflection (Single Bound) in the Infra Red, and (iii) Raman Spectroscopy. For FTIR and Raman, the intensity of the background radiation is used as an indication for the deterioration.

Many materials show little reaction. Other materials (e.g. PEN) are overstressed already after 300 hours of 1-sun according to the Raman results. With Raman, considerable effects are observed with many materials, but the interpretation is difficult. The acceleration factor for PEN transmission decrease is between 300 and 500. We have also investigated the effect of relative humidity and temperature during the exposure: a temperature increase from 20°C to 50°C causes a faster deterioration, while the humidity increase from 20 to 90% has barely a measurable effect.

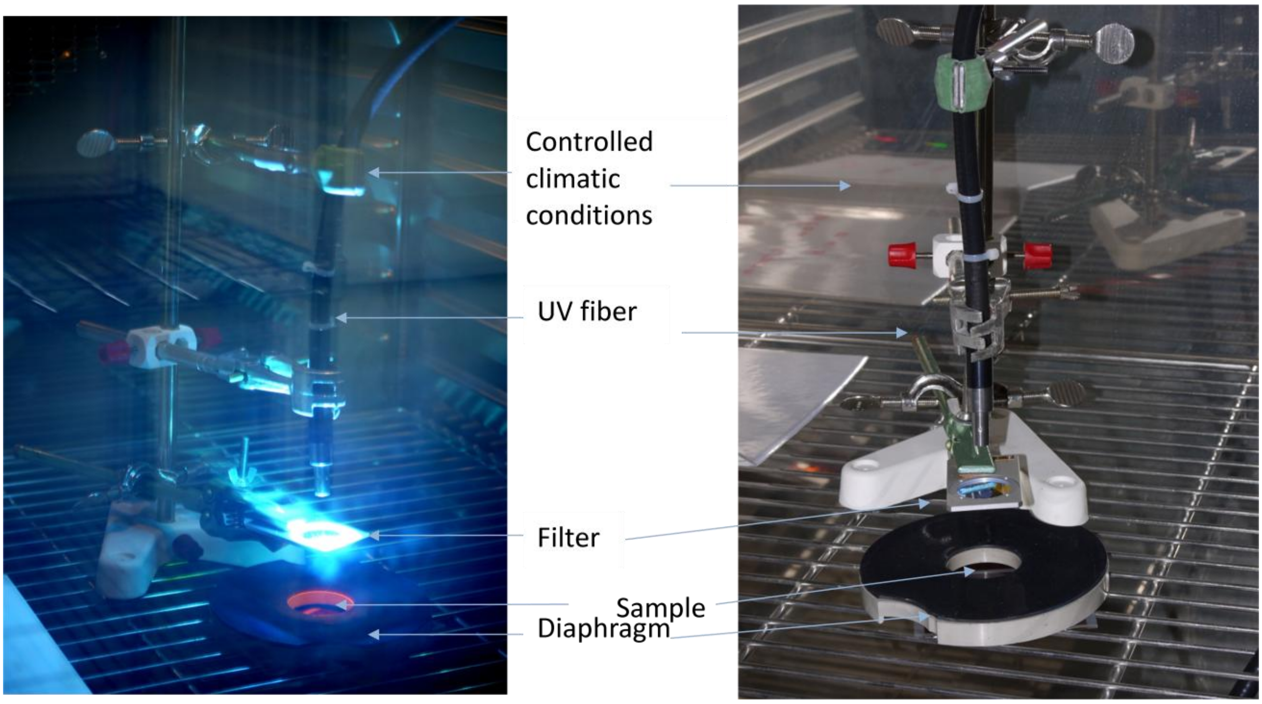

Figure 6.1: The 80-suns fast UV (FUV) set-up at OM&T.

Generally speaking, we conclude that fast UV-exposure is critical in at least two aspects: optical (e.g. avoid reflection with transparent samples) and thermal (minimize temperature variation in the sample).

We can also define two general restrictions to UV-testing. Firstly, no general interpretation of test-results is possible without knowledge of material specific properties. For example the Activation Spectrum of a polymer must be known before any conclusion around the acceleration factor of the FUV-test can be drawn. Secondly, when other degradation mechanisms besides direct UV-induced changes are involved, like radical, water or oxygen transport by diffusion for example, it is impossible to do predictions without a very elaborate study.

7 Mechanical bending

The work carried out in this team was aimed at selecting and developing methods for fast and quantitative monitoring of oxygen (and moisture) ingress linked to degradation of barrier film properties caused by mechanical stresses (e.g. stretching and bending). Both oxygen and water can trigger degradation of organic photovoltaic (OPV) devices. OPV research is often aimed at (i) designing materials that are less prone to degradation and (ii) minimizing exposure to the ambient atmosphere. The latter is commonly achieved by sandwiching OPV between "barrier" films. However, mechanical stress applied on the barrier film during roll-to-roll processing, storage and/or utilization can damage the inorganic layers (e.g. cracks), therefore increasing oxygen and water ingress [2].

Here, we evaluated methods that can potentially be used to monitor oxygen permeation through OPV barrier materials *while* the material is mechanically stressed. This type of test is completely new and can yield important additional information compared to tests for which mechanical bending and vapor ingress measurements are done separately.

Test samples are (with increasing oxygen permeation): (i) a PET or PEN film substrate only, (ii) a substrate with SiN_x layer and (iii) a complete barrier system, i.e. substrate + alternating layers of SiN_x and organic layers.

Two methods aiming at monitoring oxygen ingress though barrier films used for OPV encapsulation were evaluated: a modified version of the Mocon test and a test inspired by the so-called calcium test.

It appeared that the detection limit of the first method is insufficient to study samples with oxygen ingress levels of the range of 10^{-5}/ 10^{-6} g m^{-2} day^{-1}, the level expected for the type of samples studied.

The second strategy, which relies on the color change of a dye triggered by oxygen, displayed very promising results. A system based on methylene blue embedded in a polymer matrix was found to be a suitable oxygen sensor. This oxygen sensor could be easily solution processed in a reproducible way. The coating color change which is triggered by the reaction of the dye with oxygen was monitored by UV-Vis spectroscopy (see Figure 7.1). The color change speed can be increased by several ways, notably by increasing the temperature and/or by reducing the thickness of the coating (by e.g. using ink jet printing as processing method).

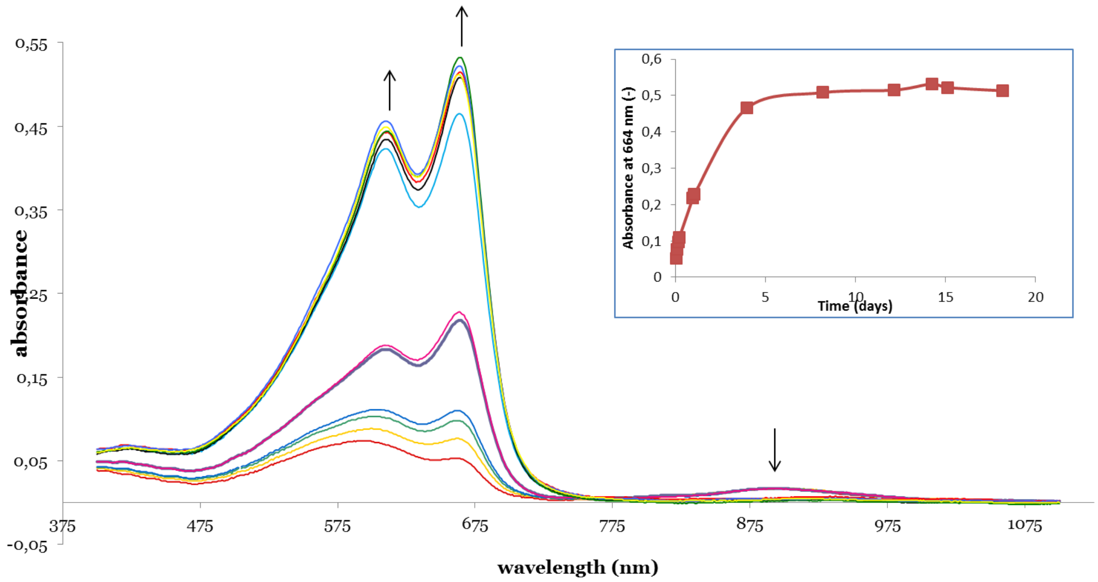

Figure 7.1: Example of the evolution of the spectrum of a coating in function of time for a 5-µm-thick film left in air at room temperature.

A follow-up of the experiments would consist of studying the change of color of the oxygen sensor encapsulated with either a PEN substrate coated by a single SiN_x layer or a PEN film on which the barrier has been deposited, before and after bending.

8 Final remarks

Within the project *geZONd*, many new test and analysis techniques for PV modules have become available to interested parties in the region South-East Netherlands. Thus, the main project goal has been reached.

Some of these techniques are (almost) unique in the world, at least for PV testing applications: e.g. the electrochemical noise test for corrosion (EcN), the core-shear test for adhesion, the thin-film humidity and oxygen sensors, the thermally-stimulated lock-in thermography and the ultra-fast UV irradiation. In other cases, the technique was known and available, but the expertise for successful application in a PV context has been created: e.g. peel testing, scanning acoustic microscopy and optical spectroscopy. The relevance of these innovations is stressed by the fact that most of them are also used in the partners' research outside the scope of this project.

Very important for faster and more efficient innovation in PV are higher acceleration factors, combined stress testing and in-situ and non-destructive characterization. Project *geZONd* has made progress on all three items.

For example, on UV irradiation, increased understanding of highly accelerated irradiation, also in combination with temperature and humidity, has been created. It has been shown that impedance spectroscopy (EIS), differential resistance and integrated humidity sensors are suitable in-situ characterization methods during life-time testing. Also the characteristic advantages and limitations of non-destructive analysis techniques like thermography, acoustic microscopy and optical spectroscopy compared to destructive analysis like cross-sectioning and peeling have been investigated.

The results of project *geZONd* have been used by the partners for publications and other exposure (see Chapter 9). The project has stimulated further cooperation between the project partners, and also between partners and other PV parties in the region. They have contributed to the set-up of the *Solliance* consortium and other projects like *Roadmap Zon op het Zuiden* and *CIGSelf*. At this moment, our region is worldwide recognized as an important PV innovation site.

Evidently, in the course of the project, the economic climate for the PV industry in Europe has become less favorable, e.g. due to very low prices of standard PV modules from China. To remain competitive, both in module production, equipment manufacturing and providing services, it is even more important now than 3 years ago to innovate fast and cost-effective. The methods and expertise developed in project *geZONd* will certainly give a competitive advantage to our region of the world.

9 Publications and presentations

SCIENTIFIC PUBLICATIONS:

- Nadia Grossiord, Jan M. Kroon, Ronn Andriessen, Paul W.M. Blom, "Review: Degradation mechanisms in organic photovoltaic devices", *Organic Electronics* **13** (2012) 432–456.
- L. van der Tempel, *Charge carrier Density Imaging / IR lifetime mapping of Si wafers by Lock-In Thermography*, Technical Note PR-TN 2011/00604 (unclassified), Koninklijke Philips Electronics N.V. 2011.

POPULAR PUBLICATIONS:

- "Vooraanstaand testlab voor Zonnepanelen", Website Brainport Eindhoven: http://www.brainport.nl/speerpunten/high_tech_systems_%26_materials
- "Zuidoost-Nederland krijgt 11 miljoen uit Pieken in de Delta-pot", Bits & Chips, 6 november 2009: http://www.bits-chips.nl/nieuws/bekijk/artikel/zuidoost-nederland-krijgt-11-miljoen-uit-pieken-in-de-delta-pot.html
- "MiPlaza pleit voor krachtenbundeling om gezamenlijke groei te realiseren", Solar Magazine, juni 2010, p28-29: http://www.solarmagazine.nl/SolarMagazine12010.pdf
- "Zonnepanelen gemarteld voor de wetenschap", ECN newsletter, october 2010 http://www.ecn.nl/nl/nieuws/newsletter-nl/2010/oktober-2010/martelkamer-voor-zonnepanelen/
- "The evolution of the Netherlands solar landscape", Solar Magazine, September 2010, special edition PVSEC Valencia, p. 10. http://www.solarmagazine.nl/SolarMagazinePVSEC2010.pdf
- "GeZONd should give Campus companies a head start in testing", High Tech Campus e-Magazine http://www.site-mail.nl/clients/high_tech_campus_eindhoven/2011_01/en_intern/intern.html

PRESENTATIONS:

- "geZONd – gezamenlijke faciliteit voor zonnepaneelanalyse en duurzaamheidstesten", J.G.M. van Berkum (Philips), presentation during Solliance event 8-12-2010 at TU/e-Campus Eindhoven
- "Kijk ver vooruit met de beste test- en analyse-strategie", J.G.M. van Berkum (Philips), presentation during Roadmap Zon op het Zuiden event 2-3-2011 at HTC Eindhoven http://www.sola-bs.nl/index.php/inhoud/35-toelichting-zon-op-zuiden, on-line presentation: http://www.solarmagazine.nl/Berkum.pdf