TNO report

Multiannual report
ETP Materials Technology 2011-2014

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Management Summary

Title: ETP Materials Technology 2011-2014
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As part of the Strategic plan 2011-2014, TNO initiated an Enabling Technology Program (ETP) Materials Technology that would result in development of generic knowledge, supporting the medium term technology needs (3-5 years) of the demand driven programmes (VP) in various TNO themes.

The activities in this ETP are the result of needs expressed in the Steering Committee for this ETP with representatives of 6 TNO themes. In retrospect the activities in 2011-2014 in this ETP have been carried out to a large degree according to the project plan developed and approved end 2010\(^1\), with annual adjustments as proposed by the Steering Committee and annual dynamics in line with MinEZ policy.

At the start of this ETP in 2011 focus was put on advanced materials for energy production as well as energy saving/storage, with main activities (use cases) on 1) energy saving and energy storage materials for the built environment, 2) materials for solid state lighting including safety by design, 3) materials for oil&gas as well as 4) materials for thin film solar cells.

These building blocks for the program have been focussed, adopted and expanded in successive steps such that in the annual plan 2014 the focus was on 1) Thin film and layered/3D printed materials with beyond conventional (meta) properties, nanostructured materials for light management in solar and safe design concepts including safe quantum dots, 2) nanomaterials with triggered and/or autonomous response for buildings and harsh environments, including binders and contrast agents, materials for compact storage of heat and light in chemical bonds and materials for optochemical sensors for harsh conditions and 3) NanoOptoMechanical solutions based on new materials, design rules and manufacturing processes such as surface probing and optical instrumentation based on metamaterials.

New activities were initiated in areas like conversion of light to energy, flow composition measurement and metamaterials. Several new (PhD) projects were initiated with external partners such as TUD, TU/e, UT, UU and NWO.

The initial development of the Qutech (Quantum Computing) initiative was supported from this ETP in 2013, leading to a joint research activity with TUD and STW in which thin film deposition and material modelling will play an important role. This activity will continue for the next years with support from NWO, MinEZ and industry.

Also together with NLR, M2i and NanoNextNL industrial needs were identified and put forward in a joint TO2/M2i materials program in 2014 ("Transitie Plan Materialen") which will be executed in the period 2014-2016 together with NLR and M2i.

The support of this ETP for future activities in TNO demand driven programmes (VP) was shaped by patent applications (>30), publications (>200) and presentations (>200) and definition of and input to various follow-up projects at the national and international (EC) level.

\(^1\) TNO-033-EH-2010-02513, proposal Enabling Technology Program 2011-2014 Materials Technology
This ETP will end by 31-12-2014 (end of the current TNO Strategic Plan 2011-2014). But the relevant technology development does not stop at such borders in time. In the next TNO Strategy Period 2015-2018 significant parts of this ETP will continue to be developed further in the framework of the TNO Early Research Programmes 2015-2018. In particular this will be the case for ERP Energy Storage & Conversion, ERP QuTech, ERP 3D NanoManufacturing, ERP Complexity (safe design of nanomaterials) and ERP Structural Integrity. Other parts of this ETP will e.g. continue in the Transitie Plan Materialen (with M2i/NLR): 3D printing, materials for harsh environments, thin film deposition.

Despite a large number of successes, we also learned from some initiatives that did not work out well (enough). E.g. the activities on recycling of electronic materials were not very successful. Partly because of insufficient progress in technology development, and partly because of changing vision in the TNO Theme. The insufficient technological progress could have been remedied by initial closer cooperation with an external knowledge partner, e.g. TUD. Another initiative that did not work out particularly well was TNO Idea, the concept of stimulation of bottom-up generation of ideas for new ETP developments. This was done in close cooperation with the other ETP programs. The initiative was successful in stimulating creativity and offered a well appreciated platform to present proposals in a competitive way, however even the winning ideas lacked the sound scientific basis needed for meaningful, ground breaking enabling development. This in its turn was likely caused by insufficient involvement and interest of senior scientists in TNO.

Finally, the ambitions in biomedical materials were not successful, despite the promising encapsulation technology developed in the BMM IDEAS project. Fortunately this technology could successfully be used for making encapsulated salts for heat storage: serendipity saved the effort!

It is concluded that ETP Materials Technology has been very successful in its ambition to provide support for the longer term technology needs of the TNO VPs in several TNO Themes by developing technology, networks out- and inside TNO and qualified personnel. These developments will continue in other ways of working, but the underlying developments will be important for the next years as they provide part of the answer to significant societal challenges as sustainable energy, the growth of the Dutch semiconductor industry, the integrity of our built infrastructure and innovations for our health and safety.

In this sense it may seem regrettable that TNO has not chosen for continuation of an integrated basic materials technology program of this kind, but has chosen for continuation in more application focused, rather independent activities without clear overall overview and thus has taken the risk of losing this integral view on materials technology as a strong enabler for future TNO activities. Given the importance, underlined by e.g. the EC giving a lot of attention to materials development in Horizon 2020, similar to the situation in the US and the Far East, some form of coordination in the materials field, even transcending the TNO organization, is strongly advised for the coming years.

The Transitie Plan Materialen gives an onset for this in the collaboration between TNO, NLR and M2i. But its effectiveness will critically depend on the level of coherence that can be organised within the Topsector policy in the Netherlands. Similarly the Chemelot initiative in Limburg, where local industry, TU/e and TNO intend to join forces on materials research, can develop into a new stronghold for this crucial enabling technology in Europe.
List of abbreviations

EC = European Community
ERP = Early Research Program (TNO)
ETP = Enabling Technology Program (TNO)
MinEZ = Ministry of Economic Affairs
VP = Vraaggestuurd Programma (TNO)
TU/e, TUD, UT, UU = Universities Eindhoven, Delft, Twente, Utrecht
NWO, STW, FOM = Research organisations in the Netherlands
TO2 = Federation of Applied Research Institutes in the Netherlands
BMM, M2i = Material Research initiatives in the Netherlands
EeB, FoF, KET = Research programs in EC (Horizon 2020)
1 Introduction

The TNO law 2005 earmarks TNO as an independent organisation to carry out applied research for the general benefit (article 4). Means to achieve this are a) research carried out by TNO, b) transfer of results, c) cooperation with other knowledge institutions, d) participation in coordination of research and international co-operation and e) execution of assigned tasks (article 5). The TNO law requires TNO to prepare a Strategic Plan every four years, in agreement with relevant governmental policy (article 19). One of the means to carry out this Strategic Plan is to carry out a Multi Annual Research Plan. Within this framework TNO has prepared Multi Annual Enabling Technology Programs (ETP) for the period 2011-2014 as well as annual plans 2011, 2012, 2013 and 2014.

The set of Enabling Technology Programs (ETP) should result in development of generic knowledge, supporting the longer term technology needs (3-5 years) of the demand driven programmes (VP) in TNO.

ETP Materials Technology has tried to realise 3 basic goals
- Incubator: the formulation of new strategic research areas for TNO as identified in discussion with TNO Themes, industry and universities, fitting in the Topsector policy developed by Dutch government.
- Excellent research: new materials and processes with demonstrated behaviour in applications.
- Expansion of collaboration with academia and other partners.

The purpose of this Multiannual Report 2011-2014 is to present interested readers
- New areas of research
- Highlights in technology development
- An overview of relations developed with industry and knowledge partners outside TNO.

This report is at the same time the annual report 2014 for this ETP, therefore quantitative output for 2014 is provided in section 3.13.
2 Execution 2011-2014

2.1 Activities 2011-2014

The activities in this ETP are the result of longer term needs expressed by various TNO Demand Driven programmes (VP) in 6 TNO themes: Industrial Innovation, Built Environment, Healthy Living, Energy, Defence, Safety & Security and Information Society represented in the steering committee for this ETP.

At the start of this ETP in 2011 focus was put on advanced materials for energy, production as well as saving in which 4 technology lines/use cases were identified:

- Sustainable durability: added value and embodied energy
  - Energy saving in the built environment
- Smart lifetime: properties and recycling
  - Solid State Lighting
- Smart surfaces: modification/optimisation/processing/safety
  - Multichemical sensors, Safe design of Nanomaterials, Biomedical materials
- Layer processing: thin film processing
  - Solar cells

These 4 lines have been focussed, adopted and redefined in successive steps such that in the annual plan 2014 3 technology lines/use cases were defined:

- Materials for controlled physical interaction with waves
  - Layered, 3D printed materials with beyond conventional (meta) properties, nanostructured materials for light management in solar and safe design concepts including safe quantum dots
- Materials for controlled chemical interaction with extreme environments
  - Nanomaterials with triggered and/or autonomous response for buildings and harsh environments, including binders and contrast agents, materials for compact storage of heat and light in chemical bonds and materials for optochemical sensors for harsh conditions
- Equipment and instruments development
  - NanoOptoMechanical solutions based on new design rules and manufacturing processes for improvement of dynamic behaviour, surface probing and optical design (e.g. diffractive optics)

2.2 Interaction (Kennisarena’s, stakeholders etc.)

The contents of the research program have been topic of discussion with various stakeholders:

- Roadmap High Tech Materials in HTS&M (including M2i)
- European initiatives (EeB, FoF, EMIRI, KET etc.)
- Universities (e.g. 3TU, UU, RWTH Aachen)
- NWO, STW, FOM, TO2
- Dutch government (MinEZ, Min Defence, Min I&M)
- Industrial stakeholders
2.3 Participation in other research programs and networks

Several projects being part of this ETP are carried out in collaboration with other initiatives and partners:

- Directly sponsored PhD positions at universities (TU/e, UT, TUD, UU)
- Part-time TNO professors at universities (TU/e, UT, TUD, RWTH Aachen)
- NWO, STW
- M2i, BMM, NanoNextNl, EC (NMP, H2020)

This participation during the period 2011-2014 annually involved about 50 PhD positions and 12 part-time positions (professorships, (U)HD) at universities.

2.4 Initiation of research activities with external partners

In 2011-2014 activities in this ETP have been undertaken to define new collaborations/projects in collaboration with universities, institutes, companies and government:

- Horizon 2020 (EC projects)
- TNO SMO (SRP, VP, B2B projects)
- TKI projects
- Hogeschool Zuyd (solar cells)
- NanoNextNl (workshops, safe design of nanomaterials)
- M2i (PhD projects)
- Universities (PhD projects)
- NWO (TKI Chemie)
- STW (OTP, Perspectief, HTSM, HTM calls)
- The QuTech initiative
- The “Transitie Plan Materialen”

Examples are included in the more detailed description of activities in chapter 3.

In the period 2011-2014 several new PhD projects were initiated with external partners such as Tule, UT, UU and NWO, who are partly finished and who are partly continuing for the next years.

The development of the Qutech (Quantum Computing) initiative was supported from this ETP, leading to a joint research activity with TUD and STW in which thin film deposition (e.g. ALD) and modelling will play an important role. Qutech was awarded the prestigious title “Nationale Icoon 2014” on November 6, 2014. (http://www.rvo.nl/nationale-icoon-2014-quantum-technologies).

In October 2013 a first proposal was prepared together with NLR, M2i and NanoNextNl to come a joint materials program in the Topsector HTSM (“Transitie Plan Materialen”). This was centred on 3 research lines (Materials for Thin Film Manufacturing, Materials for Additive Manufacturing and Materials for Constructions in Extreme Environments). Further input for these ideas was gathered in first round tables with industry in December 2013, organised together with NLR, M2i, and NanoNextNl. The final proposal 2014-2017 was submitted to the Topsector HTSM end January 2014 and formally granted by MinEZ in November 2014.

2.5 Relevance to Topsector policy

The contents of this ETP have been discussed in 2013 with Dutch government (EL&I “soft” demand driven approach) to clarify the relevance to the Dutch Topsector policy being developed in 2013. The activities in this ETP primarily are of relevance to the Topsectors High
Tech Systems & Materials, Energy, Chemistry and Life Sciences & Health. Input has been given to development of several roadmaps in these Topsectors, in particular through the roadmap HighTechMaterials in HTSM.

2.6 Quantitative output

The support of this ETP for future activities in TNO demand driven programmes (VP) can be illustrated by considering the next quantitative output data for 2011-2014:

• patent applications: > 30
• publications and presentations: > 200 peer reviewed scientific publications and > 200 congress contributions
• various follow-up projects at the national and international level multiplying the investment in this ETP by at least a factor of 2
• TNO colleagues playing a crucial role in this ETP were awarded “TNO Excellente onderzoeker”: 2012 Hamed Sadeghian, 2013 Pascal Buskens. Paul Poodt is candidate for this award in 2014.

The quantitative output for 2014 is given in section 3.13.

2.7 Continuation after 2014

This ETP will end by 31-12-2014 (end of the current TNO Strategic Plan 2011-2014). But the relevant technology development does not stop at such borders in time. In the next TNO Strategy Period 2015-2018 significant parts of this ETP will continue to be developed further in the framework of the TNO Early Research Programmes 2015-2018. In particular this will be the case for

• ERP Energy Storage & Conversion (storage of heat, conversion of light to energy)
• ERP QuTech (together with TUD in the Qutech initiative).
• ERP 3D NanoManufacturing (new processes and instrumentation, e.g. based on metamaterials)
• ERP Complexity (safe design)
• ERP Structural Integrity (multiscale modelling).

Other parts of this ETP will continue in Solliance (thin film deposition) and the Transition Plan Materials (with M2i/NLR): Materials for additive manufacturing (3D printing), Materials for harsh environments, Materials for thin film manufacturing. Also developments will continue in basic research funds available in TNO Theme Defence. At the moment of writing discussions are being held with Chemelot to come to a cooperation with TNO, in which e.g. nanostructured materials for light management and 3D printing as developed in this ETP are considered.
3 Results 2011-2014

In this chapter more detailed descriptions are given of research activities in this ETP. This is not a complete overview, but most of the work carried out in this ETP is at least touched upon.

3.1 Heat battery

There is a huge societal driver to obtain sustainable solutions that reduce energy consumption and effective use of scarce materials to achieve a sustainable society. In the Netherlands and Europe as a whole, the built environment uses almost 40% of the total energy. The ultimate goal for 2050 is to make the built environment fully sustainable: no net consumption of energy, water or building materials. For buildings to become self-supportive, it is important that the thermal energy generated in summer or during the day can be stored, and released in winter or during the night. In the ‘Energie Rapport 2011’ it was calculated that for the Netherlands only, already 42 TWh seasonal energy storage should be realized by 2050. The EU has recognized this need and has placed thermal energy storage on the agenda for the Horizon 2020 program. TNO has chosen to work on thermochemical storage systems, a new and emerging long-term thermal storage for residential use, offering high thermal storage density without the need for thermal insulation during storage.

In a heat battery, salt and water vapour are combined to generate heat in winter, and in summer, heat from solar collectors is used to evaporate the water, and the dry salt is stored.

Existing materials for thermochemical storage suffer from limited physical and mechanical stability and severe corrosion (salts), or thermal storage capacities that are too low to substantially cover seasonal storage adequately (zeolites and silica gel). The program focused on finding materials that address these issues and that enable the long-term use of these materials in a thermochemical storage environment. Encapsulation of known thermochemical materials is seen as a good potential technology for decreasing known materials’ negative properties, while retaining or even improving their positive features. A suitable encapsulation material was found, having an open structure for good vapour transport, being capable of high loading fraction and therefore still a high storage density, and being flexible, stable and cheap. Experiments have shown that encapsulation has led to
stabilization of the material, also in a packed bed, reversibility of the system and faster dehydration at 90°C. Several characterization tools were developed to support this work, including an XRD with humidity stage, nanoSEM methods, pT-diagram-o-meter and controlled hydration methods. With all the data from the characterization methods, a model was developed to understand the hydration and dehydration kinetics of the system. TNO is the first player to achieve encapsulation/preparation of salt-based thermochemical materials, which is a major advantage for collaboration with customers in B2B projects and knowledge partners in EU projects.

Important spin-off activities where this study contributes to are:

- Topsector Energie TKI project ‘Meerjarenplan Compacte Conversie en Opslag’: TNO coordinator, partners a.o. TU/e and TUD.
- H2020 EeB-6 proposal in preparation with European partners
- Materials research within the EU-FP7 project MERITS
- Setting-up a state-of-the-art experimental infrastructure (pT-diagram-O-meter, RH-stage of the XRD, controlled hydration methods, nanoSEM and TEM methods, in-situ physical stability measurements)
- Join activities on Energy Storage with ECN, TU/e (Darcy Lab)
- ERP ‘Energy Storage’ TNO 2015-2018

References/patents:


### 3.2 Photonic chemical sensing

Chemical sensors enable the control and monitoring of many processes and materials, and create routes to for better health and environmental control. The use of an optical sensor has the benefit over electronic sensors of a higher sensitivity that can be achieved and a lower sensitivity for disturbing parameters, such as hazardous chemicals and electromagnetic interference. A better control over chemical production processes will reduce costs and increase the yield. Biosensing is an attractive route towards low-cost Point-Of-Care diagnostics, with the potential of ‘fingerprinting’ a patient’s health using only a tiny droplet of blood, urine or saliva.

Two sensing technologies were demonstrated in this ETP: 1) Fibber Bragg Grating and 2) Silicon Ring Resonator; that both use the change of an optical signal in a glass fibre or silicon ring caused by a chemical responsive coating when exposed to the target analytes. For the required sensitivity and selectivity, several new chemical responsive coatings were developed and applied to the optical platform (fibre or ring). New signal processing algorithms were design for a better data interpretation and hardware was built to execute the performance tests.
The coatings that are required to make the optical sensor specific are critical for its performance. An overview was made of many coating concepts and a few were selected for further development: for the detection of humidity, CO2, hydrocarbons and other VOC’s in gas; and pH, ions and proteins in liquids. Application and adhesion solutions were developed to ensure long term adhesion and stability of the coated sensors. Three exposure systems were built: 1) a system to expose the sensors to gaseous environments at ambient conditions, 2) a microfluidic system for liquid flows, 3) a high temperature (300 °C), high pressure (300 bar) gas system.

The polymer based coatings that were developed showed good response to e.g. humidity, pH, and CO2, but have maximum service temperatures of ca. 100 °C. A large research program was defined for oil&gas applications to monitor down-hole compositions. Since, this requires higher temperatures resistance, ceramic (zeolite) coatings were designed and grown on fibres. These sensors showed responses to hydrocarbons in conditions as high as 250 °C and 200 bars. Surprisingly, no cross-sensitivity was found for water or CO2. Different zeolite-coated sensors responded differently to the hydrocarbons methane, ethane, propane, and butane. Combining various coatings will enable composition monitoring of e.g. gas under extreme conditions.
conditions. These fibre sensors are explored for use in Oil & Gas applications, environmental water quality monitoring, and indoor air quality monitoring in e.g. greenhouses.

![Figure 3.3 Optical microscopy image (magnification 50x) of a zeolite coated fibre (coating thickness = 26 μm)](image)

In collaboration between TNO and the Delft University of Technology (TUD), several experiments have been performed to demonstrate quantitative detection of proteins on ring resonator biosensors. The sensitivity was 10-fold improved by optimizing the signal processing algorithms, and provide the (patented) read-out equipment. Jointly, we quantitatively monitored the binding of various molecules in real-time with superior sensitivity. The results provide a platform for a broad range of bio-chemistries, and other ring resonator biosensing activities. The project resulted in 4 patent applications and approx. 10 publications (presentations and papers). The collaboration between TNO and the TUD on ring resonators is currently extended with the Erasmus MC and targets point-of-care detection of Influenza. B2B and H2020 projects are currently in progress or in preparation.

References/patents:
- A. Boersma, Photonic crystal sensor, WO2012125028

### 3.3 Tomographic sensing

For developments and processing of new materials, accurate sensing during the manufacturing of the new materials is crucial. Monitoring of the processing equipment is necessary to keep the process stable. Improving process control and development of new materials relies on detailed information. Therefore the focus was put on tomographic imaging of composition in (pipe) flow which offers non-intrusive measurement of local properties, like composition and
flow. This especially involves development of autonomous, accurate, quantitative and multi parameter determination of concentration of matter in liquid flows with mixtures of materials, e.g. nanoparticle suspensions, two-phase flows etc. Application domains are found in oil&gas, chemistry, pharma and food.

Figure 3.4 a) shows the basic configuration, a source transmits a guided wave in the pipe wall, this wave radiates in the liquid and refracts at different types of liquid-liquid interfaces. The wave is detected on the opposite wall. Figure b) shows the actual liquids in the cross-section and Figure c) shows the reconstructed image using numerically simulated data.

Two novel approaches developed and patented, one based on low frequency ultrasonic guided waves and the second one using a combination of microwaves and high frequency ultrasound.

With the ultrasonic guided waves, a cross-sectional image is obtained of the liquid composition inside a tube of reactor. This image shows the liquid speed of sound, which is a characteristic property of a liquid. This approach using guided waves has clear benefits over high frequency ultrasound, one being able to image much larger volumes due to lower attenuation losses. The second concept uses focused microwaves to locally heat the fluid with a specific modulation frequency. The heat is transported by the flowing multiphase liquid. The temperature changes affect the speed of sound in the liquid, which is detected with several pairs of ultrasonic sensors downstream. Because each focal point has its own characteristic modulation frequency, the measured travel time variation can be analysed for each modulation frequency by Fourier analysis separately. The measurement principle interrogates many different
properties of the multiphase flow at the same time and provides concentration and flow profile information at the same time.

The guided wave tomography algorithm has been developed completely and demonstrated on numerically modelled data, showing very good results as in the figure above. Particularly, the use of ultrasonic guided waves leads to a wide variety of applications which would not have been possible with the more traditional high frequency ultrasonic waves. This has led to the development of two novel (multi-phase) flowmeter concepts, one development has been completed and the product will be launched commercially in the very near future. Additionally the research leads to the development of a level and (distributed) density sensor where foreseen application is level and density sensing on board for LNG ships.

References/patents:
• “Separation of liquid components from a mixture”, inventors Rik Jansen, Arno Volkers, Peter van Capel, patent WO2012/064191, patent filed 10 November 2011

3.4 Responsive building materials

There is a huge societal driver to obtain durable and sustainable building materials, as well as materials that reduce energy consumption. This can be e.g. achieved by implementing responsive functionalities in building materials, like protection against micro-organisms (bacteria, fungi, and algae), signalling, and responsive pigments for heat control. To achieve these active materials, technologies are needed that release active ingredients, e.g. biocides and corrosion inhibitors, when needed. One of these technologies is encapsulation of active ingredients, which release upon a trigger, enabling material properties to be tuned. In addition, signals can be sent when a trigger is present.

Research in this ETP focused on three aspects i) understanding release and transport within host materials (e.g. coatings and plasters) ii) subsequent modification and measurement of the responsive properties, and iii) techniques that were developed to measure and determine the transport properties in materials. The latter development together with the TNO ETP Modelling program now enables us to predict release (using a model) of active substances from coatings, and encompasses valuable knowledge that now steers material development. In this period patents on modifying release of biocides were filed. The knowledge has also led, together with the EU project ‘AXIOMA’, to a patent being filed on release of biocides on tiles. As a consequence of the developed knowledge, new projects and interactions with parties have been launched with a vast group of companies.

Testing techniques for algae and fungal response tests were developed using accelerated rain tests. In addition protocols were developed to determine the chemical leaching properties of the manufactured materials. The material developments focused at different encapsulation methods (printing particles, with a suitable shell) and testing the performance of these particles. Different kinds of printed particles were developed. The challenge was to develop a method to print particles with a maximum size of 40 µm that could be cured during the time of flight, without collapsing. These particles should be mono-disperse, should have a single-core or multi-core, and are manufactured by using dispersion printing. The speed and trajectory of printed droplets under different conditions (printing velocity, printing frequency, surrounding pressure, and nozzle diameter) was calculated to predict the particle sizes, based on viscosity of the starting material. Furthermore, the time available for curing the particles and light intensity was calculated (i.e. between droplet break up and droplet collision). Subsequently, a suitable set-up was designed and built, followed by manufacturing of capsules.
A TNO-cofunded project, which has led to submission of a patent, was launched focusing on the realization of signalling coatings. In addition, this has led to the submission of an EU proposal within Horizon 2020 to the Energy Efficient Buildings call. Furthermore, a TKI-project was granted on a solar absorbing façade panel following the former initiatives. A project proposal focusing at encapsulation of actives is planned to be submitted in 2015 within Horizon 2020.

References/patents:

- Erich, S.J.F., V.V. Baukh, Modelling biocide release based on coating properties, submitted to Progress in organic coatings
3.5 Conversion of light

For the collection and conversion of solar energy into chemical energy, we decided to focus on noble metal containing nanoparticles. Through use of a smart mixture of such particles, we are in principle able to harvest the complete solar spectrum, in contrast to classical semi-conductor photo catalysts. Noble metal nanoparticles can collect sunlight and convert it into heat (photo thermal effect), resulting in a local temperature increase in direct proximity to the nanoparticle up to temperatures above the boiling point of the dispersion liquid. This local heating may be of interest for chemical conversions. In specific cases, a redox process can take place in which excited electrons on the metal surface act to occupy anti-bonding orbitals in reagents and initiate bond dissociation. On the long term, we aim at chemical conversions to produce fuels or platform/base chemicals involving such photo catalytic step.

To address this subject, we developed a lab reactor with a well-defined light source and a series of noble metal containing nanoparticles and used this for studying the solar steam generation reported by Halas and co-workers in 2013 (O. Neumann et al., ACS Nano 2013, 7, 42).
We demonstrated that upon illumination, gas bubbles are formed from gas that is dissolved in the dispersion. The bubbles are stable for seconds up to minutes, and the formation of new bubbles stops after a few minutes. This can only be explained by gas bubbles. Steam bubbles in a cold liquid cannot be stable for such long time periods, and would be formed continuously. In a reference experiment with degassed dispersion, we did not notice bubble formation upon illumination, which supports the gas bubble postulate. The work by Baffou and co-workers (G. Baffou, J. Polleux, H. Rigneault, S. Monneret, Super-heating and micro-bubble generation around plasmonic nanoparticles under cw illumination, J. Phys. Chem. C. 2014, 118, 4890) confirms this observation, and demonstrates that the steam bubble postulation of Halas and co-workers is incorrect. In spite of this, however, Baffou et al. demonstrated that upon illumination, the temperature in direct proximity of the metal containing particles increases up to values far above the boiling point of the dispersion liquid. We demonstrated that this effect can be used for chemical conversions.

The project will continue in 2015, as technology line within the ERP Energy Conversion & Storage. Within this technology line, we will focus on redox processes in which excited electrons on the metal surface act to occupy anti-bonding orbitals in reagents and initiate bond dissociation. Secondly, a project proposal on the development of an air-conditioning system powered by sunlight using the photo thermal effect studied in this project will be submitted. Thirdly, EU CO-PILOT starts January 2015. This project deals with the large scale precision synthesis of nanoparticles in dispersion. Further proposals for projects on synthesis of nanoparticles are in preparation.

References/patents:
- D. Mann, S. Chattopadhyay, S. Pargen, M. Verheijen, H. Keul, P. Buskens, M. Möller, Glucose-functionalized polystyrene particles designed for selective deposition of silver on the surface, RSC Advances 2014, 4, 62878-62881.

3.6 Light management in thin film PV

At present, photovoltaic (PV) modules have a historically low sales price which is important for their implementation as zero emission source of energy. However, first generation silicon wafer based modules, which have by far the largest share of the PV market at this moment (about 85%), are currently (partly) sold at prices below their actual production costs. To further increase the PV share in the energy market, an additional cost decrease is required making a switch to second generation, thin-film technologies necessary. These, however, need to further improve with respect to efficiency and, at the same time, significantly decrease in production costs. This requires optimisation of the optics of the solar cell to maximize the amount of photons that penetrate into the absorber layer and to increase their path length, resulting in an increased absorption.

To optimise the optics of the solar cell with the aim of maximizing the absorption in the absorber layer, tailored nanoparticles and/or nanotextured surfaces/interfaces are integrated. For that purpose, we developed a toolbox consisting of following components: (a) optical modelling using Finite Element (FEM) or Finite-Difference Time-Domain (FDTD) methods, (b) design, manufacturing and characterisation of tailored nanoparticles and nanotextured coatings/interfaces and (c) solar cell processing and performance validation.

Figure 3.7: a) Absorption in CIGS from optical modelling, (b) nanotextured resist, (c) CIGS standard (left) and with textured resist (right).
Using optical modelling, we have studied the optics of copper indium gallium (di)selenide (CIGS) solar cells with absorber layer thickness between 100 nm and 2 µm. The results of this study displayed severe optical losses in the wavelength regime between 700 nm and 1100 nm for CIGS cells with an absorber layer thickness below 1 µm. To avoid these losses, we developed a series of tailor-made metal containing nanoparticles and nanotextured resists for integration in the cell. For example, upon application of a nanotextured high-refractive index resist on the transparent conductive oxide, we realized an average increase in short-circuit current density (Jsc) of 7.2%. We strategically cooperate with the groups of Prof. Zeman and Prof. Urbach at Delft University of Technology on light management in CIGS solar cells. We exploit our toolbox in a variety of customer projects, incl. Limanil and Calm.

The developed toolbox will be used in customer projects in the field of thin-film photovoltaics involving key Solliance. Furthermore, we are currently evaluating potential other outlets such as lighting devices, optical sensing and optical data communication.

References/patents:

- Daniel Mann, Subrata Chattopadhyay, Sascha Pargen, Marcel Verheijen, Helmut Keul, Pascal Buskens, Martin Möller, Glucose-functionalized polystyrene particles designed for selective deposition of silver on the surface, RSC Advances 2014, 4, 62878-62881.

3.7 Hydrogels

Two-thirds of all people will experience at least one episode of back pain during their lifetime. Degeneration of the intervertebral disc (IVD) is generally accepted as one of the major causes of low back pain. Currently, treatment exists of physio therapeutics, and when this does not work, surgery fixing the vertebra (spinal fusion) and revalidation for weeks is the only possibility. Approximately 2 billion euro is spend in the Netherlands every year on the treatment of low back pain.

The consortium formed in the IDiDAS project, consisting of a.o. UMCU, TNO, UU, MUMC, UMCG, VUMc and TU/e has worked on the development and validation of new or improved therapies and to develop methods for tissue repair, or regenerative medicine.

Within the project, the role of TNO was the development of injectable, bioactive hydrogels. The advantage of an injectable treatment is that only a small injection is needed to heal the back pain, and no surgery. This means that less than one day in the hospital is needed for recovery. Our gel will be injected like water. The small hole caused by the thin needle will close again automatically. This is already proven in a real intervertebral disc. The body temperature will solidify the product to a gel to form a nice cushion, without chemical reactions. The cushion will
stay at the right position and will release drugs if needed. All this has been tested already in animal studies. In vivo and in vitro studies show no cytotoxicity.

Figure 3.8: To treat low back pain, thermo-sensitive hydrogels were synthesized that only gel at body temperature. Mineral particles are combined with LCST polymers, in which the mineral particles have a dual function: (1) provide additional structuring to the injectable hydrogel, and (2) act as carrier for drugs, which both stimulate cartilage regeneration and reduce pain.

It was also shown that besides controlled release of drugs, our hydrogels can also be used for the delivery of SiRNA to cells, which enables treatment with SiRNA based medicines.

Currently, clinical studies are being done with dogs with low back pain. If these tests are successful, a partner will be sought for scaling-up of this technology under cGLP conditions and market introduction.

References/patents:
• Bart G.M. van Dijk, Esther Potier, Maarten van Dijk, Marloes L.P. Langelaan, Nicole E. Papen-Botterhuis, Keita Ito, Sustained release of celecoxib reduces inflammatory mediators in a novel in vitro model of extruded disc herniation, Submitted to The Spine Journal
• Hsiao-yin Yang, Renz J. van Ee, Klaas Timmer, Eric G.M. Craenmehr, Julie H. Huang, Cumhur Öner, Wouter J.A. Dhert, Nicole E. Papen-Botterhuis, Laura B. Creemers, Injectable thermoresponsive and cytocompatible gel of poly (N-isopropylacrylamide) with layered double hydroxides facilitates siRNA delivery into chondrocytes in 3D culture, Submitted to Biomaterials
• Nicole Willems, Hsiao-yin Yang, Marloes L.P. Langelaan, Anna R. Tellegen, Guy C.M. Grinwis, Hendrik-Jan C. Kranenburg, Frank R. Riemers, Saskia G.M. Plomp, Wouter J.A. Dhert, Nicole E. Papen-Botterhuis, Björn P. Meij, Laura B. Creemers, Marianna A. Tryfonidou, Biocompatibility and intradiscal application of celecoxib loaded MgFe LDH-pNIPAAM hydrogels in a canine spontaneous intervertebral disc degeneration model, Submitted to Biomaterials

3.8 Safe design

Various stakeholders, industry, associations, authorities and research institutes need common models and the right parameters that can be applied for safe design of materials. Several parameters for toxicity cannot be used, because of interference of the nanomaterials with the method. Nanomaterials are of great importance to society, since they have shown to enhance
material properties and enable new innovative products. Nevertheless, the introduction of nanoproducts is hampered due to the unknown safety risks of nanomaterials.

The goal of this project is to include the factor safety as an item to be considered in the research and development stage of new materials. To reach this goal, demo cases are needed to show that safety by design is successful and to add information to the refinement of computational chemistry model on phys-chem properties and toxicity. New collaborations were set up with the University of Utrecht the group of A. Meijerink (materials) and J.A. Post (cell biology).

TNO has worked on 2 types of demo cases. The first demo case is on the safe design of quantum dots based on CdSe and InP. Different coatings were applied to study the influence of the coating on cytotoxicity and inflammation. A new synthesis method for InP QDs was developed using less toxic compounds and resulting in a higher yield of InP QDs. Silica coating of different thicknesses was applied to vary the size of the quantum dots from 10 nm to 50 nm to study the influence of the size on the safety of quantum dots in relation to its functionality and toxicity. Preliminary results of comparing InP QDs with silica or PEG coating showed a lower cytotoxicity and In ion leakage for the InP PEG QDs while having a higher functionality. However, these results need to be confirmed as batch to batch variations were observed.

![Figure 3.9: The uptake of QDs by RAW 264.7 cells visualized by light microscopy (left control, right cells exposed to QDs)](image)

CdSe QDs were tested in cultures of a macrophage cell line (RAW 264.7) and studied with microscopy. Fluorescence microscopy showed the uptake of quantum dots by RAW cells (see figure above). In addition, agglomeration/clustering of the RAW 264.7 cells was observed after exposure of 24h to QDs with a stereomicroscope at 40x magnification. This was not found with the metal oxide nanoparticles tested. This result was consistently found with two different batches of QDs. This aspect may have an in vivo counterpart, namely early granuloma formation, which is considered in most cases to be an adverse effect of particle exposure.

In the second demo case study several batches of latex silver nanoparticles were synthesized to study the effect of binding nanosilver particles (~30 nm) to a larger latex particle of 200 or 400 nm. Preliminary results showed a lower cytotoxicity for the larger latex particles, which should be confirmed by testing various batches.

TNO organized a workshop on safe design together with NanoNextNL for various stakeholders. From this workshop it could be concluded that accepted models needs to be designed for the determination of the safety of nanomaterials which is followed up in EC project nanoREG1. The
results also contributed to (1) the participation of TNO in several EC projects on safety of nanomaterials (GUIDEnano, FutureNanoNeeds, nanoREG1 and (2) collaboration with the University of Utrecht and RIVM.

The activities in this area will continue in various 4 years EC projects which started in 2013 and 2014. Furthermore, the project safe design will continue in the ERP Complexity and in EC project nanoREG II (proposal is submitted for phase 2).

References/patents:
• Safe design of nanomaterials – Paving the way for innovation, Dave Blank, R. van den Berg, A. Sips, G. Robillard, E. Zondervan, NanoNextNL, 2012.
• Fabriek et al. Activation of dendritic cells by exposure to nanometal oxides, in preparation
• Kuper et al. Cytotoxicity of CdSe quantum dots in RAW264.7 cells, in preparation

3.9 Miniaturised optomechatronics
In order to sustain the current capabilities and momentum in the technology roadmaps for 3D nanomanufacturing, enhancing yields and reducing the time-to-market are essential. This has to be done while simultaneously maintaining reliable manufacturing. Yields are enhanced by getting faster and higher-quality data. The process geometries and device dimensions are shrinking to the level that the conventional technologies currently used for production, quality control and inspection are approaching physical boundaries.

Conventional optomechanics technology based on classical optics and continuum mechanics theory cannot fulfil the requirements for future production and inspection, since they are at the fundamental limit of their performance.

An example is optical metrology and lithography that suffer from lack of sufficient resolution for features with nanometre dimensions. Nanomechanics based technologies such as near field methods or probe based techniques show sufficient resolution and performance at nano-scale. This research line aimed at developing technologies based on nanomechanics for future instrument development.

Scanning probe microscopy (SPM) is emerging as an essential nanoinstrument in many applications where nanometre resolution imaging and characterization are required. The ability to accurately measure critical dimensions in nanometre scale has made it an important instrument in several industrial applications such as semiconductor, solar and data storage. Examples of applications are surface roughness, channel height and width measurement, defect inspection in wafers, masks and flat panel displays. In most of these applications, the target area is very large, and, therefore, the throughput of the measurement plays an important role in the final production cost. Single SPM has never been able to compete with other inspection systems in throughput, thus has not fulfilled the industry needs in throughput and cost. Further increase of the speed of the single SPM helps, but it still is far from the required throughput and, therefore, insufficient for high-volume manufacturing.

A close cooperation with Delft University of Technology via two PhD projects financed by this programme, ensured investigation of more fundamental challenges and risks. The aim of these two PhD programme is to develop a massive parallel SPM system. Over the past three years at ETP Optomechatronics, a revolutionary concept for a multiple miniaturised SPM heads system has been developed, which can inspect and measure many sites in parallel. The very high speed of miniaturised SPM heads allows the user to scan much area, each with the size of tens of micrometres, in few seconds. Our recent experimental results have convinced us that the
time for a parallel SPM has arrived. This research line has led to over 10 internationally granted patents and 5 scientific publications in journals and on conferences. One of them was awarded as second best paper of the "European Mask & Lithography Conference 2014". Several B2B and EU projects were outcome of these developments towards reaching higher technical readiness and valorisation.

Figure 3.9: (top) Schematic illustration of parallel SPM to image several locations on a wafer or mask. Multiple positioning arms on two sides of the wafer stage, each capable of moving a miniaturised SPM (bottom) scan head on to a large sample. Many parallel miniaturised SPM heads enable full area coverage at high throughput.

References/patents:

- H Sadeghian, RW Herfst, TC van den Dool, WE Crowcombe, J Winters, GFIJ Kramer, High throughput parallel SPM for metrology, defect and mask inspection, Awarded 2nd best paper "European Mask & Lithography Conference 2014".
- H Sadeghian, TC van den Dool, WE Crowcombe, RW Herfst, J Winters, Parallel, miniaturized scanning probe microscope for defect inspection and review, SPIE Advanced Lithography, 90501B-90501B-7.
3.10 Protective materials

The project Protective Materials aims to develop a TNO tool suite for ceramic armour design and evaluation. Protection against extreme dynamic loadings like explosion and impact, set special requirements to structural design and material choice. This field of expertise is developed at TNO to support the MOD and industry in safety assessments, product evaluation and development.

Nowadays developments in material design and production are enormously and offer new opportunities for protection. Within the ETP-material program it was decided to increase the knowledge on protective materials and hybrid solutions. The focus was on the application area of ballistic protection.

In the Protective Materials project the TNO Ballistic lab (LBR), the Explosions, Ballistics & Protection group (EBP) contributed and there was a close collaboration with Delft University of Technology (DUT) (collaboration program “Impact Dynamics of Structures and Materials”). The TNO Ballistic Lab in Ypenburg is one of the top ballistic labs in the world, with advanced diagnostics to record the ballistic event (e.g. X-ray, high speed recording). EBP has the in depth knowledge on ballistics and the design of protective devices and structures at engineering level. The collaboration with DUT provides the fundamental knowledge on material modelling and failure mechanisms.

Various new materials and hybrid concepts were studied and reviewed, e.g. the application of polymers in transparent armour, a new porous concrete called “safety concrete”, as well as the potential of multi-scale modelling for dynamics. The main focus was on ceramic armour and the potential of new ceramics to realize significant weight reduction for personnel and vehicle protection.

Internationally, governments and industry invest to design and produce the ideal ceramic for armours. However, the question is: which material properties are decisive for ballistic protection? In the ballistic impact and penetration event, the material is exposed to a wide range of stress conditions varying rapidly in time and place. Experimental data on the damage development in time is scarce, and consistent data sets covering the series of damage mechanisms were not available. In the ETP project Protective Materials project we developed successfully a suite of experimental and diagnostics techniques to gather data on damage development and provide required data on the failure mechanisms in armour ceramics. These techniques are the following:

- Fragmentation test with post mortem analysis of impact damage to quantify fragment mass and size distribution.
- Spectroscopic technique to analyse the light effect and energy transition in the initial phase of the impact process.
- Time resolved visualization of crack formation during ballistic impact using high speed shadowgraphy.
- Dynamic back face deformation recording during impact.
Results for small calibre threat (7.62 AP bullets) on the various aspects of ballistic response were compared and combined with the data of the TNO energy based ballistic test method and resulted in a consistent quantitative reconstruction of the ballistic failure process. FEM analyses confirmed the armour failure mode. All these results, gained in the ETP- and related projects, were used for the development of the TNO engineering ceramic armour model.

Overall result: A computational and experimental tool suite, combining engineering and advanced techniques, is now available at TNO for the evaluation and development of ceramic armour systems for small calibre threat.

The tool suite will be applied and further developed (other threat levels) in the international EDA project Ceramball, the MOD research programme on protection of military platforms and in B2B-projects.

References/patents:
- Carton et al. (2015) TNO’s research on ceramic based armour; experiments and modelling. Int. symp. Advances in ceramics and ceramic composite materials. Daytona Beach, US.

3.11 Quantum technology

Quantum mechanics is the theory to describe the (interaction between) elementary particles. Academic research has confirmed the validity of this intriguing theory as well as many of its counterintuitive aspects. But only due to recent breakthroughs is it possible to demonstrate important quantum mechanical concepts on systems large enough to be visible to humans. The concepts of ‘superposition’ and ‘entanglement’ could now be used in a controlled way, and thereby open the path to applications like the most powerful computer ever imagined, the Quantum Computer, and communication which is inherently safe for eavesdropping, called
Secure Quantum Internet. Or as the Nobel Prize Committee formulated it in 2013: “Perhaps the quantum computer will change our everyday lives in this century in the same radical way as the classical computer did in the last century.”

The Minister of Economic Affairs Mr Kamp announced in September 2013 the start of QuTech. This institute has been founded by the Technical University of Delft (TUD) and TNO to cope with the challenges in research, development, commercialization, and coordination & cooperation with industry and institutes still ahead of us. The objective is to develop a quantum computer and secure quantum internet, and by that create significant impact on multiple Grand Challenges. Some examples:

- A Quantum Computer may finally provide the society with the required computational power to development room-temperature superconductivity and thereby provide us with lossless energy transport and storage which in its turn solves our energy shortage. The development of new medicines will be done by rigorous calculations instead of trial and error, which reduces both costs and time.
- Secure Quantum Internet is the ultimate encryption: there will be no means to listen in to secured communication. The quantum computer on the other hand, will be able to crack most classical encryption schemes. It is therefore of vital importance for the Netherlands to be one of the first countries in the world to have access to the most advanced quantum technologies. Related (Grand) Challenges are Cyber Security, Digitalization, and Safe Society.
- The Netherlands could be a centre of excellence on quantum technologies. This will be a new impulse to the Dutch economy by generating thousands of high quality, sustainable jobs. It will also lead to significant knowledge transfer to other sectors like nanotechnology, electronics, and semiconductor industry, and thereby improving the relative competitive position of our industry and safeguarding employment and creating spin-off.

During 2014 the TUD and TNO laid the foundations of QuTech, i.e. development of technical plans, contracts for cooperation, discussions with industry and closing contracts with first commercial partners. In the years 2015-2018 QuTech will make the change from academic research at the university to mission oriented development. TNO will develop a series of experimental process flows, proof-of-concept components and setups, to demonstrate the feasibility of several core technologies. From 2019 to 2030 a strong focus will be on engineering and realization of the first quantum computer. For secure quantum internet the first results are expected around 2020.
Figure 3.11: Simulations give insight in, e.g., the relationship between stress and electron mobility, used to optimize thin film stacking for functional and structural performance.

Figure 3.12: First demonstrator of RF multiplexor technology (green PCB on the left) incorporated in electronic control for transmon qubit circuits. The actual circuit is mounted in the cryostat one floor below the electronics racks on this picture.
3.12 Relations with academia 2011-2014

During the timeframe of this ETP various joint activities with academia were initialised/continued of which the tables below give an overview.

Several PhD projects were supported with cash contributions from this ETP during the period 2011-2014: All projects successfully finished by defence of a PhD thesis.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Number PhD</th>
<th>University</th>
<th>Framework</th>
<th>Period</th>
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<td>Delft</td>
<td>M2i</td>
<td>2011-2015</td>
</tr>
<tr>
<td>Degradation in SSL</td>
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<td>M2i</td>
<td>2011-2015</td>
</tr>
<tr>
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<td>Novel sensor concepts</td>
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Part-time professorships and (U)HD positions were supported at different universities according to the table below:

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<th>University</th>
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<td>Sadeghian</td>
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<td>van der Heide</td>
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<td>van Hees</td>
<td>Delft</td>
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<tr>
<td>Weerheijm</td>
<td>Delft</td>
</tr>
</tbody>
</table>

In most cases this involves a position for 1 day /week; the positions of Buskens, Sadeghian were initiated to result in a part-time professorship in 2015. Not all positions were supported for 4 years for various reasons.

3.13 Quantitive output 2014

In the annual reports 2011, 2012 and 2013 the quantitative output for publications and presentations was summarized. In order to have the complete overview the output of 2014 is given below as this report is also the annual report 2014.

Publications:

• Y. Wu, A.D. Giddings, M.A. Verheijen, T.J. Prosa, D.J. Larson, F. Roozeboom, W.M.M. Kessels, Atom probe tomography study on the optimization of Al-dopant distributions in atomic layer deposited ZnO, in preparation.
• A.P.A. Fayias, S.J.F. Erich, M. van Soestbergen, H.P. Huinink, O.C.G. Adan and T.G. Nijland, How methylhydroxyethylcellulose (MHEC) influences drying in a porous media, accepted for publication in Chemical Engineering Science
• V.Baukh, H.P. Huinink, O.C.G.Adan and L.G.J. van der Ven, Influence of Temperature on Water Sorption in Multilayer Coatings, submitted for publication in Progress in Organic Coatings
• “FT-IR and 29Si-NMR for evaluating aluminium–silicate precursors for geopolymers”, Materials and Structures, Published online 30 October 2014
• D. Mann, S. Chattopadhyay, S. Pargen, M. Verheijen, H. Keul, P. Buskens, M. Möller, Glucose-functionalized polystyrene particles designed for selective deposition of silver on the surface, RSC Advances 2014, submitted.

• M. Segers, N. Arfsten, P. Buskens, M. Möller, A facile route for the synthesis of sub-micron sized hollow and multiporous organosilica spheres, RSC Advances 2014, 4, 20673-20676.


• V.Baukh, H.P. Huinink, O.C.G. Adan and L.G.J. van der Ven, Influence of Temperature on Water Sorption in Multilayer Coatings, submitted for publication in Progress in Organic Coatings


• Mirjam Theelen, Krista Polman, Mathieu Tomassini, Nicolas Barreau, Henk Steijvers, Jurgen van Berkum, Zeger Vroon, Miro Zeman, Influence of deposition pressure and selenisation on damp heat degradation of the Cu(In,Ga)Se2 back contact molybdenum, Surface & Coatings Technology 252 (2014) 157–167


• RJF Bijster, J de Vreugd, H Sadeghian, Phase lag deduced information in photo-thermal actuation for nano-mechanical systems characterization, Applied Physics Letters 105 (7), 073109.

• Hommen, Gillis; de Baar, Marco; Duval, Basil; Andrebe, Yanis; Le, Hoang Bao; Klop, Wimar; Doelman, N; Witvoet, Gert; Steinbuch, Maarten, “Real-time optical plasma boundary reconstruction for plasma position control at the TCV Tokamak”, Nuclear Fusion 54, 2014.


Presentations and proceedings:


• Y. Wu, S.E. Potts, D. Giddings, M.A. Verheijen, F. Roozeboom, W.M.M. Kessels, ‘Towards an in-depth understanding and a significant enhancement of the doping efficiency of Al-doped ZnO films’, 14th International Conference on Atomic Layer Deposition. (ALD 2014), Kyoto, Japan, June 15-18, 2014.


• Dennis Snelders, poster International Conference on Sensing Technology in Liverpool, 2-4 September 2014.

• Bob Dirks, Shell/Polytec conference “measuring by light”, Brussels, 4th December 2014


• M. Segers, M. Sliepen, N. Arfsten, P. Buskens, M. Möller, A facile and versatile platform approach for the synthesis of sub-micron sized hollow and multiporous organosilica spheres, MRS Fall Meeting 2014, Boston (USA), accepted for poster presentation.

• M. Segers, R. van Zandvoort, M. Sliepen, N. Arfsten, M. Verheijen, H. Keul, P. Buskens, M. Möller, A facile and versatile platform approach for the synthesis of sub-micron sized hybrid particles with programmable composition, size and architecture, MRS Fall Meeting 2014, Boston (USA), accepted for oral presentation.

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• Mirjam Theelen, Supratik Dasgupta, Nicolas Barreau, Jurgen van Berkum, Zeger Vroon, Miro Zeman, The influence of atmospheric species on ZnO:Al degradation, 6th Photovoltaics Thin-Film Week (2014) in Berlin


4 Signature

The Hague, 3 March 2015

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