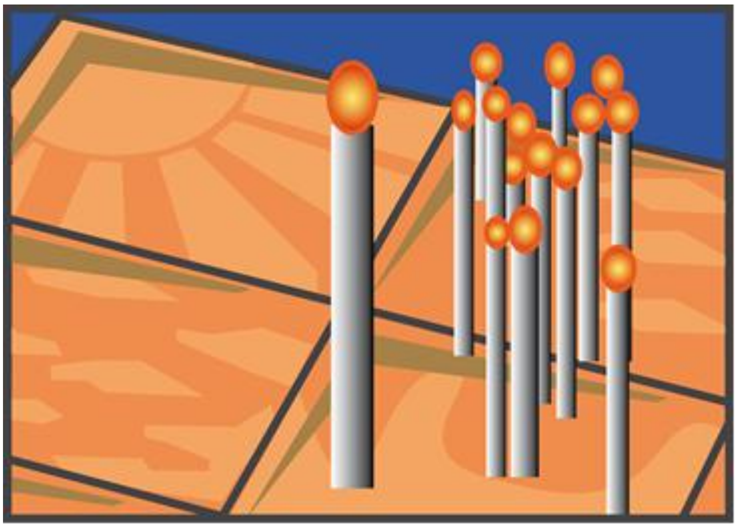
PROJECT FINAL REPORT



Grant Agreement number: **227497**

Project acronym: **ROD_SOL**

Project title: **All-inorganic nano-rod based thin-film solarcells**

Funding Scheme: **Collaborative Project STREP**

Period covered: from January 1, 2009 to December 31, 2011

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the grant agreement

[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm ; logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

Content

Final publishable summary report

I. Executive summary

Title: ROD_SOL

Grant agreement no: FP7-NMP-227497
Start and end dates: 01.01.2009 - 31.12.2011

Co-ordinator:
Institute of Photonic Technology, Germany, Dr. Silke H. Christiansen, e-mail: silke.christiansen@ipht-jena.de , phone: +49 1796894182, fax: +49 3641 206499
· Simulation of cell concepts, VLS-CVD growth of Si nanorods, p-n junction development, chemical etching of NRs, TCO contacts using ALD, electrical and optical characterization

Consortium:
Friedrich-Alexander Universität Erlangen-Nürnberg, Max-Planck Research Group, Germany
· VLS-CVD growth of GaN and Si NRs,
EMPA - Swiss Federal Laboratories for Materials Testing and Research, Switzerland
· Chemical etching of NRs, electrical electrical, optical, and mechanical characterization of NR ensembles and individual NRs, electrochemical deposition of TCO
Hungarian Academy of Science, Research Institute for Technical Physics and Materials Science, Hungary
· Determination of structural properties of NRs (TEM)
AIT – Austrian Institute of Technology GmbH, Nano-System-Technologies, Austria
· Metal templates for VLS NR growth, optimization of TCO layers by magnetron sputtering
VTT Micro- and Nanoelectronics, Finland
· Metal templates for VLS NR growth, fabrication of NRs using RIE, optimization of TCO layers by ALD, doping by diffusion following ALD deposition of dopants
PICOSUN oy, Finland
· Optimization of TCO layers by ALD, doping by diffusion following ALD deposition
Aixtron AG, Germany
· VLS-CVD growth of GaN and Si NRs, optimization of CVD equipment
BiSOL d.o.o., Slovenia
· Determination of solar cell parameters, demonstration of a device based on NR material
iSupply Deutschland GmbH, Germany
· Technology watch of thin film photovoltaic technologies and benchmarking the ROD_SOL results

Objectives: The project has explored new innovative concepts for thin film solar cells based on nanorods (NR). The nanorods were fabricated either by the vapour-liquid-solid (VLS)-CVD growth method on various substrates such as Si-wafer and glass or by wet chemical etching or reactive ion etching of thin multi-crystalline Si layers on glass or Si wafers. The VLS growth has been reached by statistical or patterned metal templates and yields dense ensembles of randomly oriented single-crystalline NR. The NR diameter of choice and dopant concentration for optimum solar cell efficiencies was derived based on numerical simulations and on experiments. The most promising synthesis method for high efficiencies and best large area manufacturability has been identified. The materials optimization is based on structural, optical, electrical, and mechanical characterization of the NRs.

The targeted thin film solar cell processing of NRs includes many materials optimization steps like the realization of axial or preferably radial p-n junctions and the deposition of transparent conductive oxides as front contacts.
Technology watch of thin film photovoltaic technologies and benchmarking the ROD_SOL concept with respect to other thin film technologies as well as validation of the NR based solar cell material has been carried out.
First thin film devices were realized on small area substrates within the duration of the project. Further research is needed to upscale the processes and to improve materials properties to approach the efficiency of planar wafer based materials.

II. Summary description of project context and objectives

II.a Concept and project objectives

Semiconductor NRs in solar cells are suggested more recent with the convincing offer of applicability in solar cells as antireflective films and as active elements in organic dye-sensitized and inorganic solid-state devices. In ROD_SOL we have made use of NRs as the active absorber material in an all-inorganic thin film solar cell and thus created a novel, 3D device architecture that needed strong research to develop all the components needed to fully exploit the potential of that cell.

Concept

The ROD_SOL project has aimed at making available to the markets of novel materials and nanomaterials for energy applications a thin film material based on silicon NRs. Materials developments and optimization based on NRs have been one of the major tasks in ROD_SOL next to the integration of these NRs in working thin-film solar cell devices, their testing and benchmarking of solar cell parameters. The leading European materials oriented groups have contributed to this task together in one project. Innovation has taken place in areas of materials processing of NRs such as adequate preferably radial doping, NR contacting based on conformally wrapped around transparent conducting oxide (TCO) layers. These materials developments were guided by device simulations.

The goal of ROD_SOL is to realize optimized thin film material systems based on semiconductor NRs that show photovoltaic behaviour and properties optimized for that application. The NRs can be grown or realized bottom-up or top-down.
In ROD_SOL we will essentially try to optimize and understand the bottom-up so called vapour-liquid-solid (VLS) growth process first described by Ellis and Wagner in 1963. The VLS growth process is based upon a droplet of a metal/semiconductor alloy that catalyzes the local growth of a NR which is a shaft of the semiconductor material. This NR crystallizes with the diameter of the catalyzing droplet and the NR pushes the metal alloy droplet away from the substrate when, upon supersaturation with semiconductor species from the gas phase (e.g. silane, DTBS) the semiconductor shaft crystallizes on the substrate.
The catalyzing metal nano-droplet template determines the VLS process a lot and metal template optimization using for comparison Au, Pd, Al and Cu will be a task in ROD_SOL. The preference is for metals that do not contribute deep traps in semiconductors, therefore Al or Pd are in favour, but reports on successful NR growth are quite rare. However, processing is difficult with these metals (oxidation and silicide formation problems). Au and Cu induce deep traps in silicon, but processing of NRs is well established. Gold (Au) works easiest for silicon NR growth at comparably low growth temperatures (eutectic temperature of Au-Si alloy system is 363°C) and the largest body of literature of almost 10 years is available. A strategy of which metals to be in favour for the processing of solar cells (minority carrier device, cost efficiency an issue) will be derived in ROD_SOL. Thick and thin metal layers can be used determining the size of the droplets that will form upon heating and liquefying and thus determining the NR size. As a last option we also look

into the integration of NRs of a direct bandgap material from the group-III nitride systems in a thin-film solar cell. This approach is highly novel and opens up the option to satisfy absorption in the direct bandgap material with possibly even thinner films that in the Si NR case. The commercial RTD as well as production type reactors available in the consortium (high temperature CVD tools, MPRG, AIX) allow the growth of these NRs at elevated temperatures. GaN-based NRs will be grown on directly on silicon wafers or on Si NRs that themselves reside on Si wafers. These GaN-based NRs grow by VLS on Si wafers so that for integration onto glass or foil, the depilation strategy described before needs to be followed.

As VLS NRs are not the easiest achievable semiconducting nanostructure it is also an option and will be tested in ROD_SOL to etch (top down) NRs into silicon wafers and depilate them from the wafer while being able to re-use the wafer several times. In any case we will be using the etched NRs that can easily be produced at larger volumes to provide these NRs essentially in the beginning of ROD_SOL to the partners to establish the different characterization techniques (electrical, optical, mechanical- after embedding).

For the integration of NR in thin film solar cell device concepts additional processing steps and properties need to be developed:

(i) Metal nanotemplates for the VLS CVD growth of NR ensembles
(ii) p- and n-doping of NRs (axial and preferably radial)
(iii) realization of back and front contacts with low contact resistances and good transmission properties: optimizing transparent conductive oxide (TCO) films covering the 3D NRs surface
(iv) passivation of large surface area using CVD (e.g. atomic layer deposition) (additional passivation layer between TCO and semiconductor NR may be needed)

care for sufficient absorption in the thin indirect semiconductor film of indirect silicon (or direct InGaN): optimize NR ensembles (random or patterned, growth directions, etc. to account for multiple scattering in NR ensembles).

For comparably complex highly challenging materials optimization at the nano-scale overall sophisticated characterization is key for the success of materials developments. Techniques to be used are structural, electrical, optical and mechanical characterization of individual and NR ensembles. The 3D NR materials optimization for the envisaged application can only be successful when supported by numerical simulations

Strategic objectives

- To enable seven world class research institutions (including a leading group from the USA) to realize based on basic materials science a novel nano-material based on semiconductor NRs for the application of a thin-film solar cell concept that has the potential for high efficiencies (>15%) at competitive production costs.
- To transfer results from basic materials developments in research directly to two equipment manufacturing companies that transfer materials developments/processes into technological relevance at a scale needed in production lines.
- To validate and benchmark the novel NR-based thin film material at an end users test site and compare it to other bulk and thin film concepts that are continuously monitored at a consulting company specialized in PV technology watch.

Scientific objectives

- semiconductor (mostly Si) NR deposition or integration on glass or foil substrates need to be developed and among different options of deposition/synthesis such as bottom-up and top-down methods the most promising one with the potential for best materials/device properties, best up-scalability at lowest production costs needs to be identified;

- Identification of the most suitable material based on numerical and physical device simulations and experimental solar cell parameter extraction based on electrical measurements (ensembles and single processed NRs) is needed;
- establishment of physical device simulations for the novel 3D NR-based solar cell using the COMSOL and r-soft or ATLAS simulation software;
- establish parameter extraction from electrical measurements that need to be established for single processed NRs and NR ensembles (preferably also at an end user test site-BISOL);
- materials optimization based on combined structural, electrical, optical and mechanical characterization by TEM and SEM techniques, I-V measurements based on 4-point-probe measurements or AFM-tip based contacting of single NRs in an SEM and contacting processed NR ensembles, as well as optical characterization in an integrating sphere of wavelength dependent light absorption or optical standard characterization for solar cells at the end users site as well as mechanical tests of stability of single processed NRs and reliability tests of embedded NR-based thin films with respect to delamination, bending, cracking and disintegration of components.

Technological objectives

The integration of selected processes in a technological process or processing environment (up-scaling needed) with the potential to yield a highly efficient and cost effectively to be produced thin film NR based solar cell on cheap substrates need to be carried out at three industry/SME sites. These industry partners carry on the tool and process optimization/modification and the following technological objectives can be derived from industry partners' tasks:

- AIX, PICO and BISOL are requested to support optimized NR synthesis and NR processing (doping, contacting, integration on cheap substrates) based on the evaluation of materials developed by the research partners;
- AIX, PICO and BISOL are requested to support the transfer of processes into a technologically viable environment;
- AIX, PICO and BISOL are requested to support materials characterization of optimized materials from institute partners using optimized standard characterization techniques available at their sites for their internal materials/process developments;
- BISOL and iSD are requested to support the benchmarking of the novel ROD_SOL thin film material compared to current bulk and thin film concepts that are partly already in production;
- tool and process developments for the (MO)CVD deposition of NRs by the bottom-up VLS mechanism at different temperatures is needed;
- tool and process developments for the TCO deposition by either ALD, spray pyrolysis, magnetron sputtering is needed;

Policy objectives

Today, European companies can compete in the PV market (bulk and thin-film materials). The technology leadership in thin-film photovoltaic could potentially be gained by the accumulated knowledge and expertise in Europe once research and development is financially supported. ROD_SOL will enable a European solar module producer (BISOL) to possibly advance the novel NR based thin film PV concept and prepare it with the help of the strong, multi-disciplinary consortium for a future generation of thin-film PV and make it attractive for the thin film PV market. ROD_SOL also supports European equipment manufacturers (AIX, PICO) that deliver equipment for materials processing most suited for all sorts of novel thin film and composite materials and in particular also for the NR-based thin-film processing needed for the proposed concepts. For these equipment manufacturres it will be extremely attractive to commercialise their tools in a tremendously growing field of green energy.

III. Description of the main S&T results/foregrounds

WP 1: Elaborate different cell concepts for an all-inorganic, air-stable, NR based thin film solar cell on glass or flexible metal/polymer foil based on simulations

WP 1 main objectives were the following:

- To develop useful input decks / module combinations in the software to treat the NR-based material;
- To establish optimized layer thicknesses /NR dimensions / cell layouts for a highly efficient solar cell application making use of numerical simulations;

Main innovative results:

An optimization procedure has been performed during the course of the project, in order to determine optimal values of rod radius R and rod length L of Silicon Nanowire (Si-NW) based solar cells. Optimal parameter pairs R and L were found for two types of contact configuration (Fig. A) assuming symmetrical doping situation with density of 10^{18} cm^{-3} both in the p-type core and the n-type shell of the rod (see Fig. B).

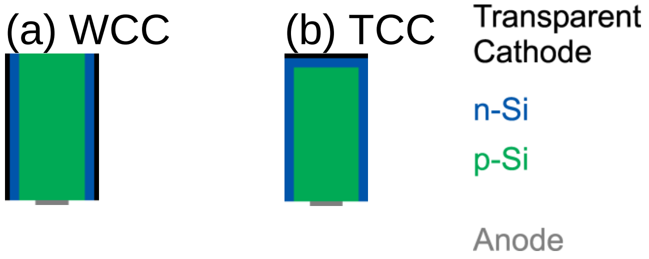


Fig. A: Sketch of 2 types of contact configurations explored in simulations. (a) Wrapped Contact Configuration (WCC). (b) Top Contact Configuration (TCC).

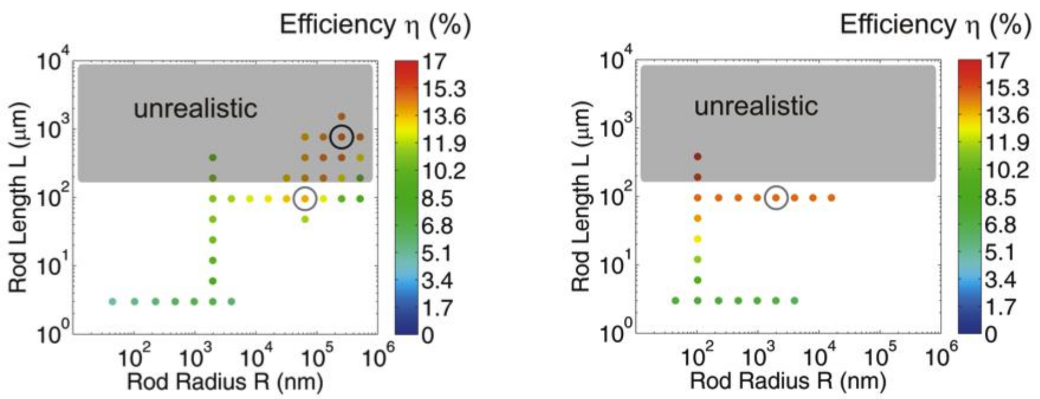


Fig. B: Optimization procedure of rod radius R and length L. (a) Wrapped Contact Configuration. (b) Top Contact Configuration.

Optimum rod radii were determined to $R_{opt}^{(WCC)}$ = 64 µm for the Wrapped Contact Configuration (WCC) and $R_{opt}^{(TCC)}$ = 2 µm for the Top Contact Configuration. Rod lengths had to be restricted to values L < 100 µm to stay in an experimentally feasible range, otherwise the assumption of a

Lambert-Beer-like absorption within the wires would have led to unreasonably large rod lengths. Under these assumptions, solar cell efficiencies at AM1.5G illumination of $\mu_{opt}^{(WCC)}$ = 13.9% and $\mu_{opt}^{(TCC)}$ = 15% were extracted. Top Contact Configuration turned out to be superior to Wrapped Contact Configuration, on one hand because of higher estimated cell efficiency, on the other hand, because the values of extracted optimal radii of 2 µm appear experimentally more viable than the ones of 64 µm.
The demand that the space charge regions (SCRs) within radial pn junction nanowire solar cells has to be well-formed and comprised within the radial dimensions of the wire, is a major prerequisite for good solar cell performance. Therefore, general type asymmetric space charge regions in cylindrical pn junction solar cells were investigated by a half-analytical half-numerical approach. Results of minimal radii to comprise the whole SCR are shown in Fig. C.

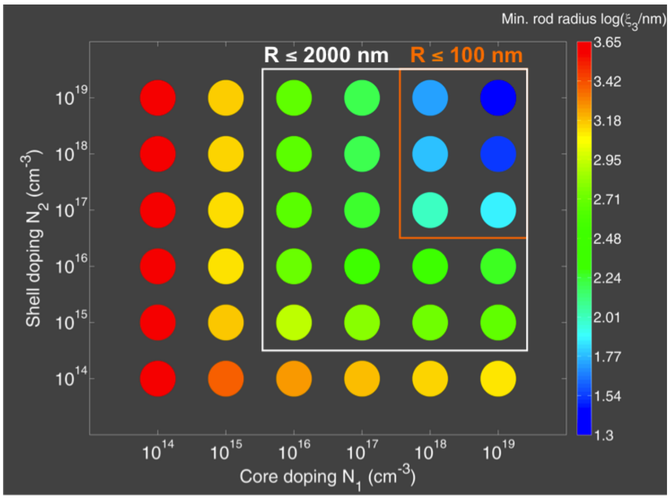


Fig. C: Necessary minimal radii for asymmetrically doped Si-nanorods shown vs. core doping N_1 and shell doping N_2. Radius is displayed in color coding, numbers show logarithm to the base 10 of the radial value in nm.

The results lead to the conclusion that small radii (≤ 100 nm) of Si-NWs can be used only with high doping (≥ 10^{18} cm^{-3} for the core, ≥ 10^{18} cm^{-3} for the shell). This is in contradiction with the approach to use Si-NW-based solar cells prepared by template-less Metal Assisted Wet Chemical Etching (MAWCE) of silicon, because for high doping a rather porous structure is produced instead of a nanowire-like microstructure. On the other hand template-less MAWCE is a favored fabrication process for the nanowire carpets, due to its simplicity and due to very strong broad-band light trapping offered by this material, owing nanowire radii below the 100 nm range.

The Semiconductor / Insulator / Semiconductor (SIS) concept offered a way to use template-less MAWCE as absorption layer deposition technique, nevertheless. The concept consist in a layer system of a Al-doped ZnO coating, a thin tunneling barrier of Al_2O_3 of approximately 1 nm thickness, and the absorption medium consisting in wet chemically etched nanostructured silicon. The working principle of a SIS heterojunction, tunneling-based solar cell is shown in Fig. D by means of band diagrams for idealized case of optimally chosen dipol layer energy offsets. Minority carriers tunnel through the oxide barrier into the ZnO:Al, while majority carriers are extracted at a contact attached to the nanostructured silicon. The working principle is old – it was discovered and described in the line of the Metal / Insulator / Semiconductor (MIS) solar cell concept investigations by M. A. Green and coworkers in the 1970s – but the application of the concept to silicon nanostructured solar cells in new. Efficiencies of Si-NW solar cell prepared according to the SIS concept, which are based on nanostructured silicon, surpass the ones prepared with radial pn junctions by far. Details about the Whys and Hows of the good performance of SIS concept based nanostructured silicon solar cells are still a matter of ongoing research in this fascinating area of nanowire-based silicon optoelectronics.
(a) (b)

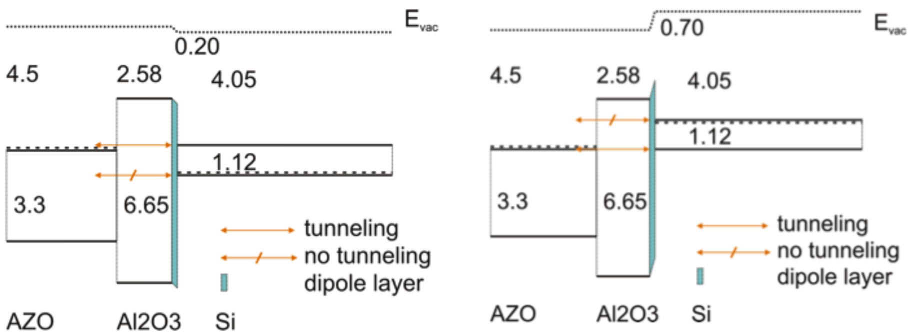


Fig. D: Band structures of planar SIS diodes before leveling of quasi-Fermi energies in materials. (a) structure with p-Si, (b) structure with n-Si.

Conclusions:

Silicon nanowire based solar cells optimized by simulations show up largest efficiencies with rods owing radii in the range of 2 µm. These structures can in principle be prepared by *Vapor Liquid Solid* growth or *template-mediated* MAWCE, but the effort is large. A simpler process, which has the scope to be commercially applied, is template-less MAWCE. However, smaller rod radii in the 100 nm range and below are obtained here. Within the radial pn junction concept, doping densities larger than 10^{17} cm^{-3} would have to be utilized for such small radii, which is in contradiction with the MAWCE method, producing rather porous structures without nanowire-like features for such high doping densities. However, the Semiconductor / Insulator / Semiconductor (*SIS*) concept turned out to work very well with nanostructured silicon prepared by template-less MAWCE, starting with weakly doped silicon material.

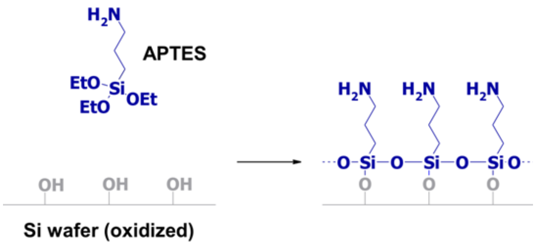
WP 2: Development of metal templates allowing for high density and preferably larger diameter VLS nanorod growth either on glass or Si-wafer

Essential preparatory work for the self-organized growth of nanorods was done in work package WP2. This work is of common interest for the steadily growing VLS (vapour-liquid-solid) growth community. The following methods have been developed and established:

a) Metal nanoparticles from different materials (Au, Al, Ni) as templates for the VLS growth of nanorods: both immobilization of nanoparticles and vacuum deposition with subsequent annealing on different substrates
b) Lithographic patterning of metal templates
c) Self-organized growth of nanorods without any metal catalysts

Regarding issue a), Au nanoparticles have been used to fabricate large diameter (up to 250 nm) Si nanorods. The Au nanoparticles were immobilized from colloid solutions on different substrates after surface modification using APTES (Fig. 1). The thin silane film terminated with amino groups electrostatically attracts the negatively charged Au colloids and leads to the immobilization of the nanorods on the substrate. The density of the nanorods can be controlled by different concentrations of colloids in the liquid whereas the distribution of the colloids was random in the plane.

The second method of film deposition and subsequent annealing to form nanocrystals has the advantage of a clean process which is totally carried out under vacuum conditions.



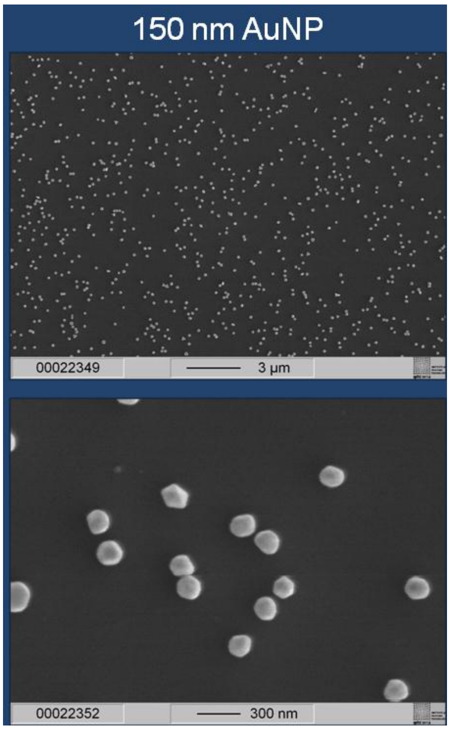


Fig. 1: Left: Surface modification of Si wafer by APTES (3-aminopropyltriethoxysilane) for better adhesion. Right: Distribution of Au colloids immobilized on APTES Si surface.

While a homogeneous distribution of equidistant equal-sized nanorods is optimally aspired, the above listed self-organized approaches usually are less perfect in this sense. In general, the main reasons for patterning of templates are the controlled growth of rod/wire arrays for the photovoltaic applications. The potential advantages are the homogeneous growth in terms of uniformity, thickness and inter-rod distance preventing shadowing effects and matching electronic transport parameters with rod diameters. Several solutions for patterned templates have been exploited in the RODSOL project: an approach to e-beam-patterned Si oxide on Si wafer, nanoimprinted patterns as masks for Au dot production, and SiO_2 and PS (polystyrene) spheres template for metal patterning.

The synthesis of ordered arrays of gold nanodots by nanosphere lithography was carried out by the transformation of a honeycomb mask to hexagonal nanoparticle arrays while paying attention to the crystallinity, size and shape of the Au particles (fig. 3). Due to the substantial influence of temperature and annealing atmosphere on diffusion and mobility of Au on silicon (Si) substrate and on the surface states of Au, the controllability of the organisation, morphology and crystallinity of these nanodots in different atmospheres (Ar, N_2, Air, H_2 and vacuum) and at different annealing temperatures was studied. This study opened the way to control the mechanism of the thermal annealing of different supported metals as a function of the chemical composition of the supported surface, the temperature and the atmosphere (fig. 4).

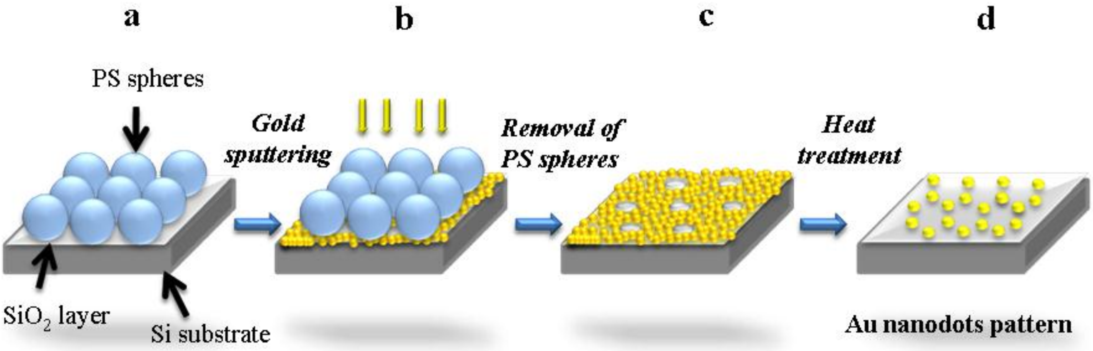


Figure 3. Schematic drawing of the realization of Au nanodot arrays using PS sphere patterns as a shadow mask for Au sputtering. (a) - (d) show the different processing steps.

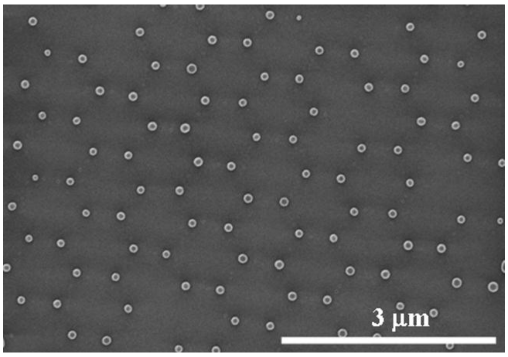


Figure 4. SEM image of Au nanodots. After sputtering 200 nm of Au films, the PS spheres were etched away and thermal annealing in Ar for 2h (heating rate 10 °C min^{-1}) at 1000°C was carried out. Doubling the thermal annealing time at 1000°C provides hexagonal arrays of Au nanodots without visible satellite nanodots between the center nanodots. The diameters and thus the volumes of the Au nanodots in these patterns appear highly homogeneous from SEM

As another example of patterned template growth, MOCVD was used to grow GaN pyramids on GaN/sapphire substrate using a pre-patterned SiO_2 mask (fig. 5). The SiO_2 was deposited for 5 minutes in a sputtering system. With lift-off technique holes were prepared into the mask. The growth of GaN was continued by MOCVD.

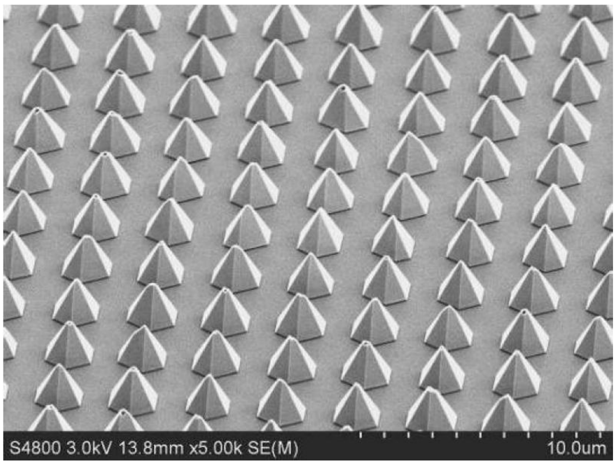


Figure 5: GaN pyramids on pre-patterned SiO_2 mask on c-plane sapphire substrate grown in MOCVD reactor.

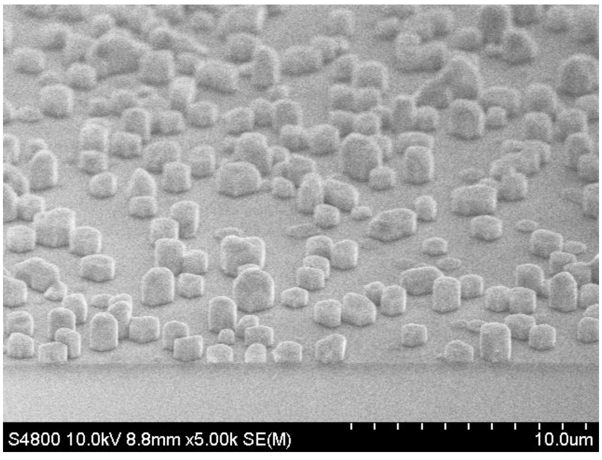


Figure 6: SEM picture of GaN nanorods without using a metal catalyst and a mask. The hexagonal structure indicates the growth in c-direction. The view is 60° tilted to the surface normal.

In addition to the patterned templates, a purely self-organizing process was studied to realize a catalyst- and mask-free growth of GaN nanorods, carried out by MOVPE. First, a sapphire substrate was annealed at 1200°C for 10 minutes in a NH_3 atmosphere. GaN nanorods were then grown in H_2 atmosphere at a temperature of 1150°C - 1200°C. The results show hexagonally shaped nanorods (fig. 6). The sidewalls are perpendicular to the surface. These structures can be extended in the vertical direction without any coalescence to neighbouring nanorods.

WP 3: Single crystalline, defect-free, high density NR VLS growth by CVD processes

The main objective of WP3 was the establishment of CVD growth processes for Si NRs and InGaN NRs and the optimization of NR morphology in this processes for the envisaged application.

Main innovative results:

IPHT, AIXTRON and MPRG were involved in WP3. The IPHT concentrated on the growth of vapor-liquid-solid (VLS) Si NRs using CVD. AIXTRON focussed on VLS grown (In)GaN NRs by vertical flow MOCVD. MPRG developed a catalyst-free method to synthesize (In)GaN NRs by horizontal flow MOCVD.
IPHT has utilized a cold wall CVD system to grow VLS Si NRs at a temperature of ~510 °C using Silan as a Si precursor and Au as a catalyst. NR structures with a diameter up to 250 nm were achieved. The Si NRs are random oriented. Solar cells containing VLS Si NRs were processed showing poor efficiencies below 1%. It is expected that the use of catalyst material leads to impurity incorporation into Si resulting in dramatical reduction of the solar cell efficiency. The low efficiency compared to the etched NWs, which are discussed in other WP sections, shows that VLS grown Si NRs are not suitable for photovoltaic device applications.
AIXTRON has developed MOCVD processes for the high temperature growth of GaN based NRs on GaN/sapphire templates. All experiments have been performed in a R&D type Close Coupled Showerhead (CCS) MOCVD reactor with a capacity of 3x2 inch wafers or 1x4 inch wafer. As Ga-precursors Trimethylgallium (TMGa) as well as Triethylgallium (TEGa) have been used and NH_3 as N-precursor. For the NR growth the catalyst initiated VLS mechanism has been used. As substrates sapphire templates, beforehand coated with gold films, have been used. The Au droplet diameter and density, defining the final NR diameter and density, depends on the original Au-film thickness, which was varied between 0,2 nm and 2,5 nm. The growth temperatures have been varied between 800 °C and 1030 °C, the reactor pressure between 50 and 900 mbar, the V/III ratio from 3 to 50. The extreme low V/III-ratios are the main difference compared to 2D GaN film growth. After NR growth the Au droplet is still visible on top of each wire (Fig. 1, TEM) proving that VLS growth really occurs. But, as confirmed by TEM analysis from MFA, the droplet is much smaller than the NR diameter. A growth model was developed to explain the different diameters of Au droplets and NRs, which was not expected from pure VLS growth mechanism theory. Aside from this anomaly the NRs showed the desired shape – steep flanks and for c-axis oriented GaN typical 6-fold symmetry. The polarity of all Au initiated GaN NRs was N-polar. The NR shape (tapering), diameter and density was influenced by the main growth parameters V/III ratio, reactor pressure and growth temperature.
Based on optimized growth conditions for GaN NRs, GaN/InGaN core shell growth experiments have been performed. Already the quality of the first grown NRs was good enough to generate room temperature (RT) photoluminescence (PL). Fig. 2 shows the RT PL of three samples deposited at 700 °C, 720 °C and 740 °C, respectively. As known from planar InGaN quantum well (QW) growth, the In concentration increases with decreasing growth temperature resulting in a red shift within the PL spectrum. Further process optimization resulted in the demonstration of core-

shell structures with a 3-fold GaN/InGaN MQW showing RT PL emission. UV microscope inspections have proven that the large area homogeneity across the 2-inch wafers was good.

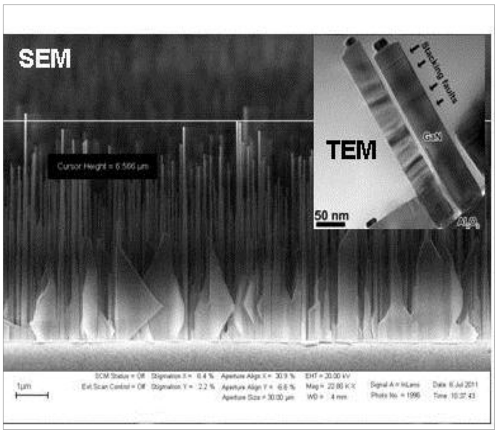


Figure 1: SEM and TEM picture of GaN NRs deposited via VLS growth on GaN/sapphire templates with optimized growth parameters.

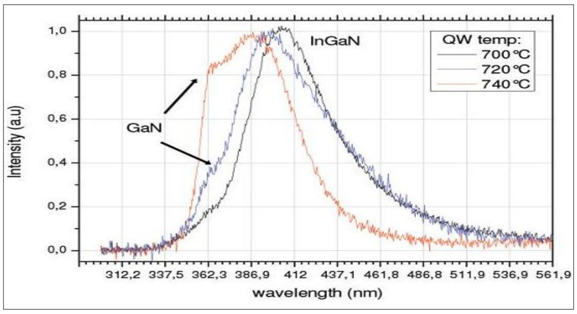


Figure 2: Room temperature PL of InGaN-GaN core-shell structures deposited at 700 °C, 720 °C and 740 °C by MOCVD / 266nm Nd:YAG, ~1 W/cm².

The MPRG concentrated their activities on the MOCVD growth of catalyst-free and mask-free GaN NRs. In order to keep the fabrication costs as small as possible a simple process was applied. Sapphire and Si(111) were used as substrates for GaN without any previous processing, i.e. no masking, no catalyst deposition and no chemical treatment was performed. The GaN NR growth method itself consists of just two – three main steps resulting in a simple and reproducible process.

The growth process consists of nitridation of the sapphire surface, deposition of a GaN nucleation layer (NL) and growth of GaN NRs. All steps were carried out at high temperatures between 1150-1200 °C (thermocouple temperature measured inside susceptor). An example of self-catalyzed GaN NRs is shown in Fig. 3. All rods and NRs are vertically aligned and exhibit smooth sidewall facets. In case of a two-step growth mode without the deposition of a GaN NL regular hexagonal shaped rods have been achieved. In between the rods there is no additional GaN deposition visible. After deposition of a GaN NL for 1 s the formation of GaN NRs takes place. Increasing the NL time to 4 s leads to a higher density (~10^8 cm^{-2}) and a reduction of the diameter. With this procedure a large morphological variety can be adjusted: NRs diameters in the range from 100 nm to a few µm, heights up to 40 µm and aspect ratios up to 40.

The optical properties of single NRs reveal a modulation of the GaN near band edge emission (NBE) and the yellow defect band due to the appearance of whispering gallery modes. Additionally, decreasing the growth rate leads to suppression of the yellow defect band and to enhancement of the NBE. The results pointing out the high structural and optical quality of NRs.

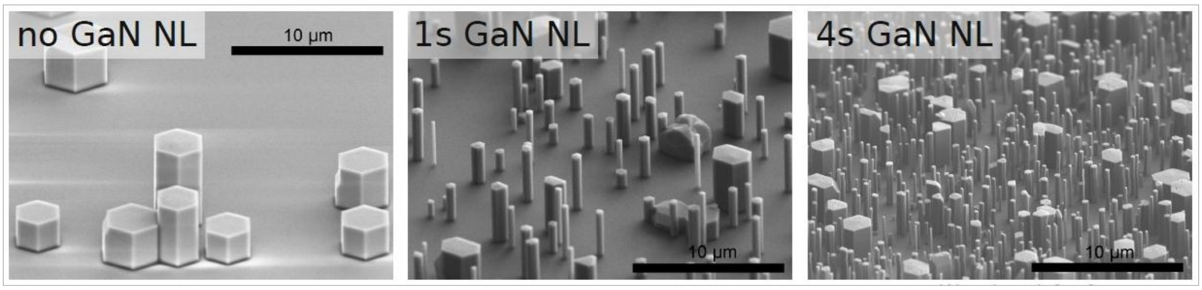


Figure 3: Scanning electron microscopy images of GaN nanorods on sapphire are shown. Left: without deposition of a GaN nucleation layer (NL); center: 1 s GaN NL deposition; right: 4 s GaN NL deposition.

InGaN QWs have been deposited around the NRs having an emission wavelength of 420-450 nm, depending on the growth temperature.

Progress of GaN NRs grown on Si(111) substrates was achieved. To some extent vertically aligned GaN NRs have formed. However, pyramidal structures and tilted NRs are also present on the surface.

Conclusions:

The bottom-up growth of VLS Si-NWs is not suitable for the integration into photovoltaic devices due to low efficiencies. The top-down etching process of a Si substrate leading to NR formation seems to be the more promising technology.
The growth of (In)GaN NRs either with a catalyst-induced VLS growth mode or a catalyst-free growth method was successful and a large variety of structural morphologies have been achieved. The GaN NRs were covered with InGaN QWs acting as an optically active material. Optical characterization revealed QW emission in the blue/violet spectral range for both VLS and catalyst-free grown NRs. However, the indium content in the QWs is still to low to have sufficient light absorption of the solar spectrum. Nevertheless, the successful integration of InGaN is an important step towards an InGaN/GaN NR based photovoltaic device.
Basically, the growth of NRs was carried out on non-conductive sapphire. In order to contact the bottom side of the GaN NRs and to reduce production costs it is desirable to use Si substrates. First progress reveal a partial coverage of GaN NRs on Si(111) showing that the growth of NRs on Si(111) is in principal possible.

WP 4: Chemical etching of NRs in Si-wafers and development of depilation and embedding and re-integration processes of embedded NRs on glass or foil

In the project proposal, the main objectives of WP4 where defined as follows:

- developing NR formation by etching of Si wafers
- developing receipts for the realization of different NR diameters
- developing receipts for the control of NR surface roughnesses

- development of NR embedding and depilation process for integration of that material in a thin film solar cell

The main focus of this relatively small work-package was put on the development of top-down etching processes for the fabrication of NW and NR arrays on Si wafers. Two different approaches where pursued for this purpose. The first approach consists of etching random arrays of NWs by the help of a continuous layer of Ag nanoparticles. The silicon wafers covered with Ag nanoparticles were immersed in an etching solution; the Ag particles sag into the silicon and leave behind a dense array of high aspect-ratio NWs. The process sequence is visualized in Figure 1; Si NW brushes realized with different etching parameter sets are depicted in Figure 2.

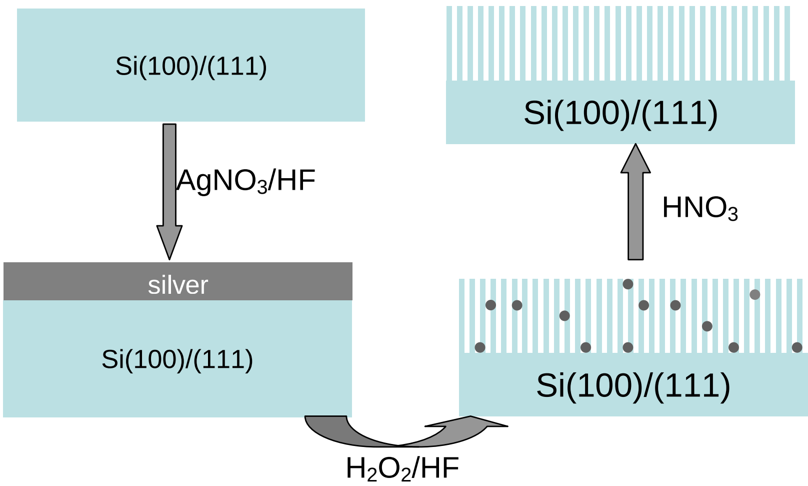


Figure 1. Schematic illustration of the etching process of silicon wafers using a sequence of two solutions; solution I is based on $AgNO_3$/HF and solution II is based on H_2O_2/HF. After solution I treatment, a quasi-continuous Ag layer forms (schematically indicated by a layer named silver) on the silicon surface consisting of densely aligning Ag nanoparticles.

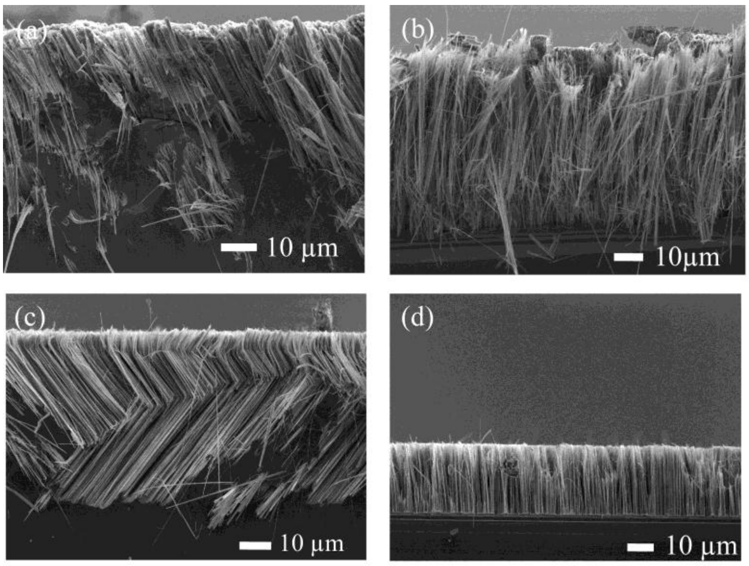


Figure 2. (a)-(d) SEM cross sectional micrographs of SiNW arrays formed **via** wet chemical treatment of Si(111) by Ag nanoparticles with different process parameter sets.

The second process route developed in this work-package is the templated etching of Si NR array with a patterned metal layer. In a first step, an array of polystyrene (PS) spheres is deposited onto the Si surface. In a thermal treatment, the PS spheres are bonded to the substrate and shrunk so that a metal layer can be deposited in between the spheres. After the etching step where the silicon below the metal layer is dissolved, a regular array of Si pillars remains standing where the PS spheres avoided the deposition of the metal catalyst layer. The diameter and the interdistance of the NRs can be controlled by adjusting the heat treatment parameters on the PS sphere template. By varying the etching time, NRs of different aspect ratio can be realized, see Figure 4.

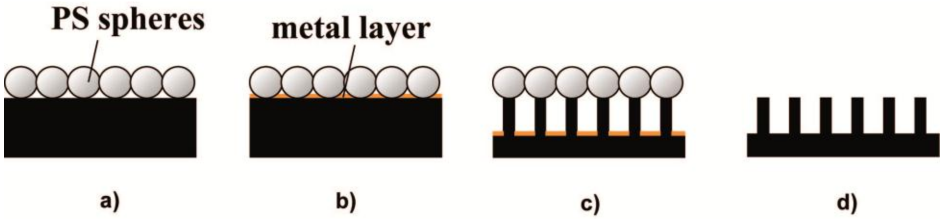


Figure 4 Process sequence of the templated etching of Si NRs. (a) a one dimensional array of PS spheres is deposited. (b) a metal layer is deposited between the PS spheres either by electroless plating or by magnetron sputtering. (c) the silicon under the metal layer is etched. (d) the metal and the PS spheres are removed.

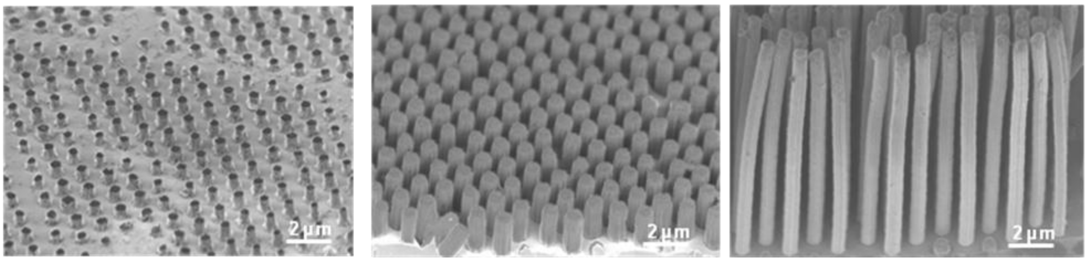


Figure 4. NR arrays with different lengths and aspect ratios.

A preliminary study on the embedding of Si NWs in polydimethylsiloxane or polyetoxy derivates showed promising results. We used the polymer to stabilize the Si NWs and depilate them from the single crystalline silicon wafer as shown in the SEM micrograph in Figure 5. However, the reintegration of the depilated Si NW array into a working thin film solar cell device proves to be difficult. As an alternative approach for the production of thin film PV devices, the top-down etching Si NW/NR arrays into macro-crystalline Si thin films is a promising option.

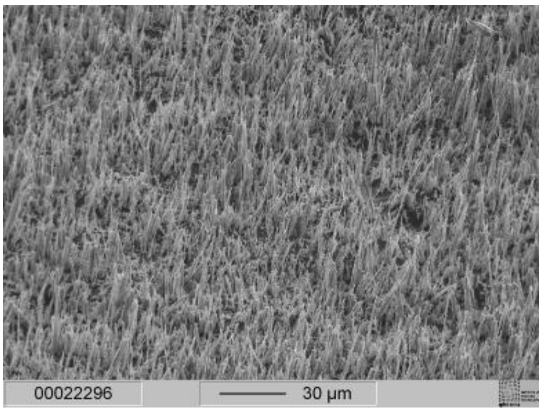


Figure 5. SEM micrograph of the etched wet chemically etched SiNWs transfered into

polydimethlysiloxane (PDMS) by the depilation of etched nanostructures form the single crystalline silicon wafer.

The realized Si NR arrays have been used in order to investigate different solar cell concepts. In a first concept, a semiconductor-insulator-semiconductor (SIS) layer sequence is produced by Atomic Layer Deposition (ALD) onto a Si NW array randomly etched by Ag nanoparticles. Further on, the Si NW arrays have been used to realize organic/inorganic hybrid solar cells. From ordered NR arrays realized by templated etching with PS spheres, devices have been realized by covering the Si NRs with an Al-doped ZnO (AZO) layer by ALD, thereby creating a p-n junction between the Si rods and the AZO layer. The solar cell concept and the characterization of the realized structures are described detail in other work-packages.

WP 5: pn-junction development (axial and preferably radial) by doping Si-NRs: development of doping procedures (co-doping during CVD, in-diffusion)

WP 5 main objectives were the following:

- development of p- and n- doping of NRs by co-doping during CVD processing (axial);
- development of p- and n- doping of NRs by diffused doping following ALD deposition of dopants (radial);
- development of p- and n- doping of NRs by diffused doping following spin on glass deposition (radial);
- development of p- and n- doping of NRs by deposition of doped a-Si and subsequent recrystallization (radial);

Main innovative results:

Silicon Nanorods insitu doping

SiNRs grown by the vapor-liquid-solid method using gold as a catalyst were doped using increased dopant precursor (PH_3 and B_2H_6) to silane (SiH_4) ratios. The crystal structure of Si-NRs was investigated by transmission electron microscopy (TEM). The CVD-grown Si-NRs have a diameter of ~ 170 nm, are single crystalline, and the only extended defects are twin boundaries parallel to the growth axis (**Fehler! Verweisquelle konnte nicht gefunden werden.**1). The NRs are surrounded by a thin amorphous layer (~2 nm), which is probably due to the growth of native oxide during the exposure of the NRs to the atmosphere prior to imaging. No additional NR sidewall growth (tapering) can be observed for p- and n-type doping for the concentrations used.
For measuring the electrical properties of NR ensembles ohmic contacts were made to the n-Si backside using evaporated Ti/Ag (5/200 nm) and to the p-Si backside using evaporated Al (200 nm). The front side of the substrate with the Si-NRs sticking out of the surface was contacted by pressing the NR film onto a glass substrate covered with transparent conductive oxide (ITO). I-V characteristics of doped NRs and axial p-n junctions were measured in the dark and under AM 1.5 illumination conditions. p-n junctions were realized between NRs and the substrate as well as axially in the NRs separated by an intrinsic segment. The dopant concentration of the Si substrates and the intended doping concentration of the NRs was ~10^{18} cm^{-3}.
However, no clear diode like behavior (as shown below) of the devices can be observed anymore probably due to degenerately doped NRs. The doping gases B_2H_6 and PH_3 were used at low (100 ppm in He) and high (2% in He) concentrations. Clear rectifying behavior can be observed for the resulting devices (Figure 2). The I-V curves for NRs grown with a lower dopant concentration in the process gas show lower forward currents (higher series resistance) and a higher reverse leakage current in the dark, as compared to NRs grown with a higher dopant concentration. Furthermore,

the diode ideality factor decreases and the open-circuit voltage V_{oc} slightly increases with increasing dopant concentration. This is consistent with the results of simulations, which show an increasing V_{oc} with increasing the dopant concentration in a range of 10^{15} to 10^{18} cm^{-3}. However, the still very low V_{oc} values are probably due to the low quality of the p-n junction and therefore a high trap density near the junction.

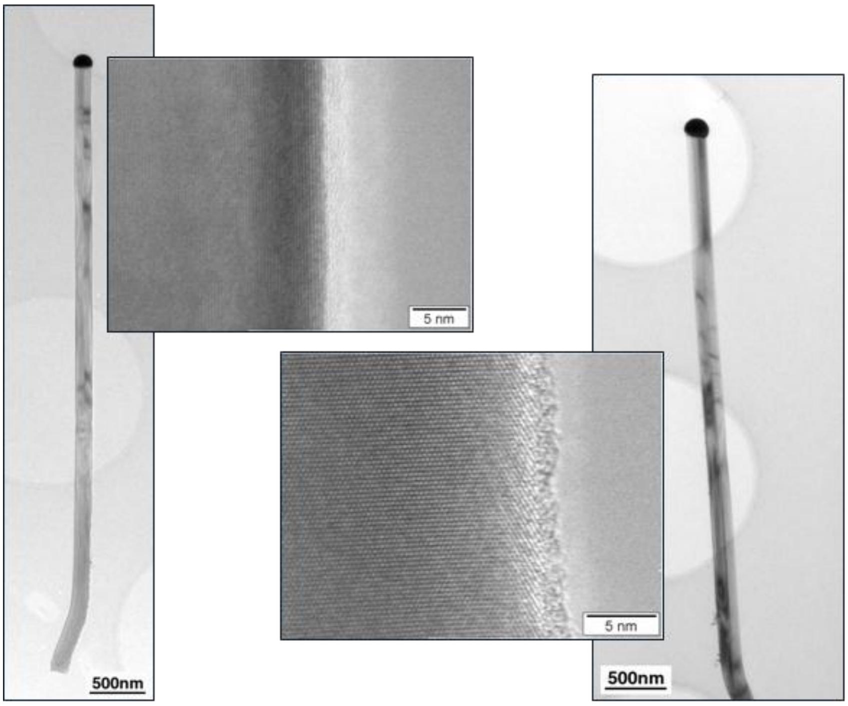


Figure 1. *TEM and high resolution TEM images of a boron-doped SiNR (left) and a phosphorus-doped SiNR (right).*

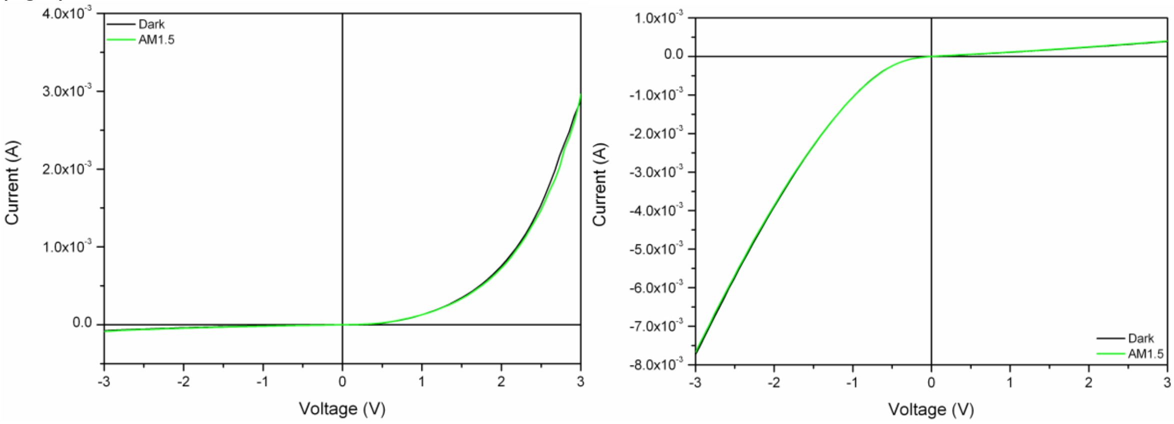


Figure 2. *I-V curves of axial p-n junctions fabricated with boron-doped SiNRs (left) and phosphorus-doped SiNRs (right) using a high concentration of dopant gases during VLS-CVD growth.*

Electron beam-induced current (EBIC) imaging was used to demonstrate the successful activation of the dopants for individual nanorods, and current-voltage (*I-V*) measurements show the rectifying behavior of the p-n junctions. The dark spot seen in the right inset of Figures 3 and 4 indicates an EBIC flowing from the substrate (n-type) to the Pt-Ir tip through the boron-doped SiNR, and the junction is located at the nanorod-substrate interface. *I-V* curve shown in Figure 3 is rectifying with the forward direction from the Pt-Ir tip to the nanorod. For a phosphorus-doped SiNR grown on a p-type silicon substrate a bright spot indicates an EBIC flowing from the Pt-Ir tip through the nanorod to the substrate with the junction located at the nanorod-substrate interface, and a rectifying *I-V* curve with the reverse direction from the Pt-Ir tip to the nanorod (Figure 4).

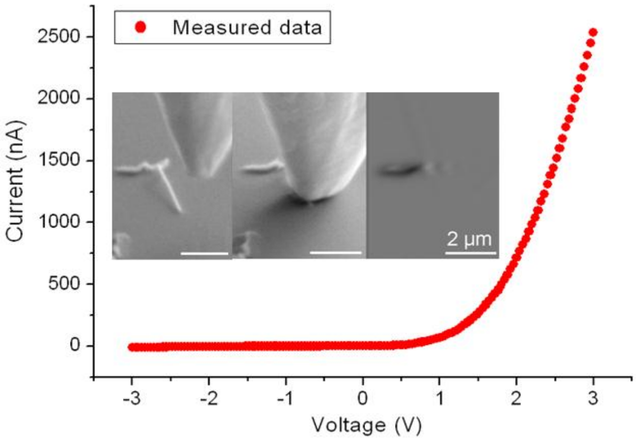


Figure 3. *Current-voltage characteristics measured on a boron-doped nanorod grown on an n-type substrate as shown in the left inset. Center inset is a secondary electron (SE) image of the tip in contact with the nanorod. Right inset is an EBIC image of the p-n junction located at the nanorod-substrate interface (dark spot).*

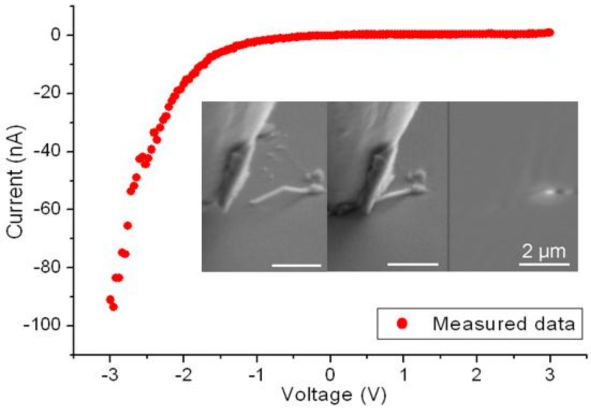


Figure 4. *Current-voltage characteristics measured for a phosphorus-doped nanorod grown on a p-type substrate as shown in the left inset. Center inset is a secondary electron (SE) image of the tip in contact with the nanorod. Right inset is an EBIC image of the p-n junction located at the nanorod-substrate interface (bright spot).*

To measure the electrical properties of individual NRs the geometry of metal contacts fabricated using e-beam lithography is currently optimized. To estimate the concentration of incorporated dopant atoms the resistivity of SiNRs has to be measured by the four-probe method. Therefore, SiNRs were transferred on an oxidized silicon substrate and were individually contacted using electron-beam lithography. The contacting of NRs requires several steps like deposition of NRs from a colloidal phase on the pre-patterned substrate, determination of exact positions of NRs with a SEM or optical microscope, design of the contact geometry with CAD software, spin on, exposure, and development of e-beam resist, treatment with hydrofluoric acid to remove the native oxide shell around the NRs, thermal evaporation of contact material, and lift-off the resist. All these steps were performed under clean room conditions to avoid contamination. The pre-patterned substrates contained 26 patterns, each with 20 contacts, and an inner area of 200x200 µm², where NRs can be contacted (Figure 5). The contact geometry as well as the resist and metal layer thickness have to be adjusted to the NR diameter. However, the following problems should be solved in future:

- What influence has the contact geometry on Schottky barrier height?
- Which metals/metal stacks are the best for minimizing the contact resistance?
- How important is an etching process prior to the contact deposition?
- What is the ideal contact thickness to wire diameter ratio?

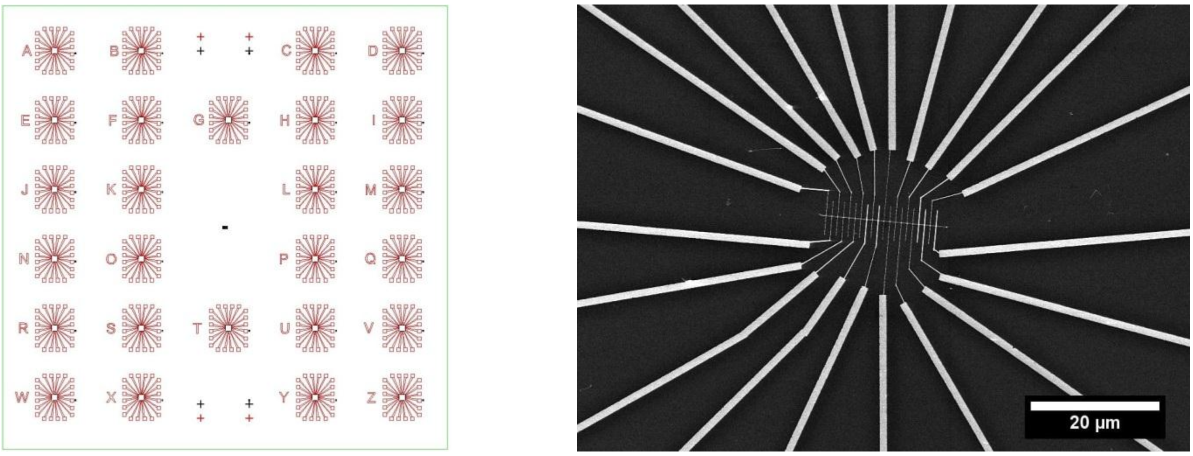


Figure 5. *Design of the prepatterned substrate for contacting SiNRs (left) and SEM image of a NR contacted by metal electrodes in a multi-terminal layout (right).*

Si wafers of different doping levels were etched using a mixture of $AgNO_3$ / HF followed by etching with a H_2O_2 / HF mixture (5 s / 4 min). Alternatively, wires were grown by CVD using 150 nm diameter Au nanoparticles. After removing Au and the native oxide from the wires a-Si was deposited at a heater temperature of 700°C using silane and B_2H_6 as a doping gas. The thickness of a-Si films was measured using ellipsometry giving a growth rate of ~5 nm / min for highly p-doped layers (700°C, 4 sccm SiH_4, 1 sccm B_2H_6 (2 % in He)). The a-Si layers with a thickness in the region of 100 nm were crystallized using a tube furnace at 700°C for 1 - 6 h, leading to a polycrystalline Si shell.

The characteristics of solar cells based on etched wires from wafers having different doping levels and the influence of active cell area on solar cell parameters has been studied. An increased doping level of the core leads to an decrease of V_{oc} and J_{sc}, whereas a decreased cell area gives strongly improved solar cell parameters.
A first homo-junction cell based on lowly n-doped VLS-wires with highly p-doped shell, however, did not show any solar cell behavior. With a developed set of standard parameters IPHT produced a homojunction p-Si/n-Si solar cell on wet-chemically etched silicon nanorods. Therefore ~150 nm p-type a-Si was deposited onto the n-type NRs and crystallized by annealing for 6h at 700°C. As a front contact 400nm ALD-AZO was deposited. The I-V-curve was measured under a sun simulator, and the serial resistance was subtracted out by fitting a one diode model to the measured curve and by setting the serial resistance to zero. This leads to an efficiency of about 4 % (see Fig. 6).

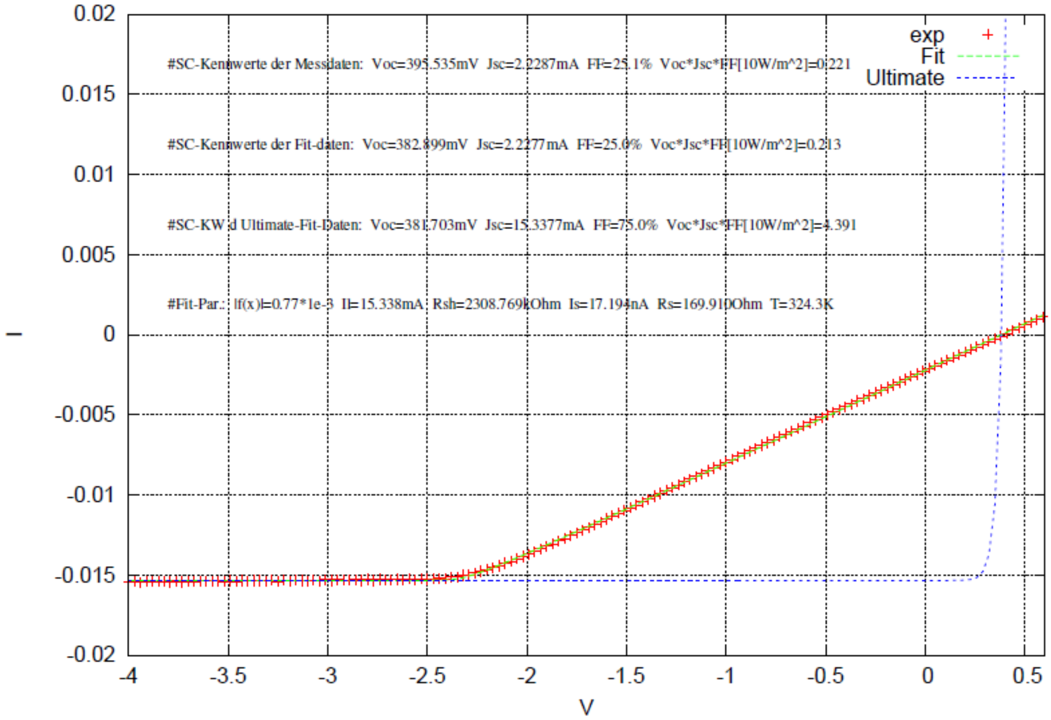


Figure 6. Measured and corrected I-V curve of the homojunction solar cell on silicon nanowires.

The structure and electronic properties of the solar cell were investigated by SEM and EBIC measurements. As can be seen from a plain view SE image the sample preparation is homogenous over a relatively large area. There are no dark spots with a high density of recombination centres or with bad charge carrier separation in the EBIC image (Fig. 7).

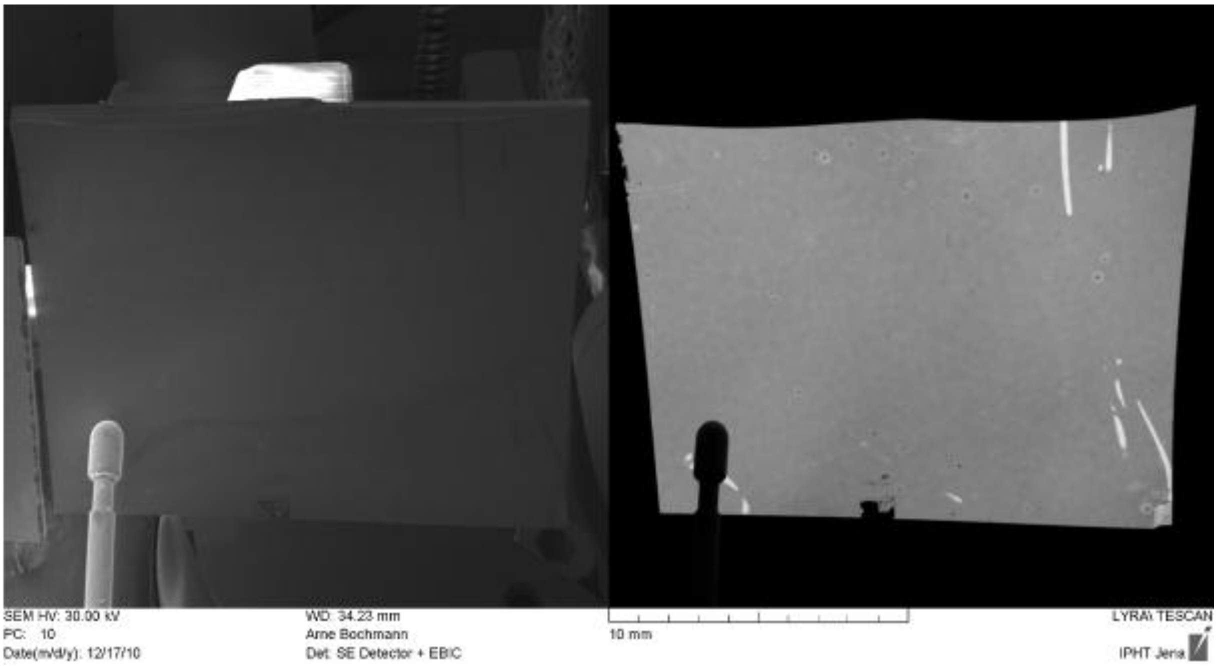


Figure 7. SE and EBIC images of the homojunction solar cell on silicon nanowires.

After polishing a cross section with the FIB we further investigated the cell. One can clearly see, that the nanorods are covered by a relatively thick layer of silicon followed by the TCO, as shown in Fig. 8. EBIC reveals that charge carriers are separated in the nanorods (bright signal). However, the separation efficiency seems to be slightly smaller as compared to the bulk material. That means, that the nanowires contribute to the cell performance electronically but there might be a higher density of defects due to the large interface area.

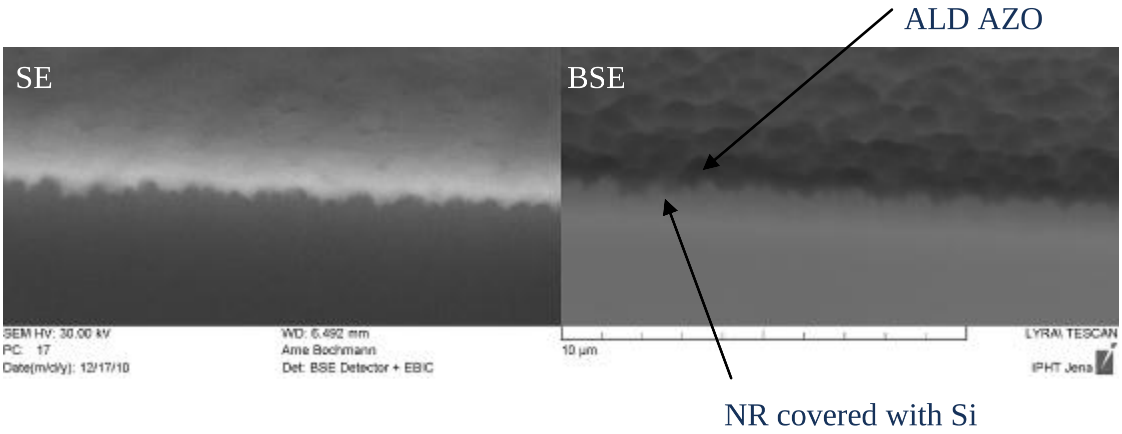


Figure 8. SE and EBIC images of a cross section of the homojunction solar cell. One can clearly distinguish between the TCO and the nanorods covered by recrystallized a-Si.

Radial doping with ALD solid source diffusion

Atomic layer deposition (ALD) is a gas-phase deposition method which enables deposition of conformal thin films on complex nanostructures. The doping of the silicon nano- or micro-rods by ALD is based on the deposition of conformal thin films (e.g. metal oxides) containing the n- or p-type dopants on the desired surfaces and subsequent annealing to drive in the dopant into the silicon. During annealing dopant atoms are diffused into the crystal lattice of the substrate and after annealing the remaining dopant source film is removed. Radial doping with ALD solid source was tested with antimony, which is an n-type dopant in silicon. Sb is a relatively large atom with small diffusion rate in silicon and is therefore it is mainly used in special applications where really shallow doping profiles are required. It is usually incorporated into silicon with low energy ion implantation, which naturally cannot be employed in 3D structures and solid source doping from Sb_2O_4 at temperatures far above 1000°C has also been employed. Despite slow diffusion, the activation energy of Sb is small, leading to a full activation of dopants already at 700°C. Also the molecular simulations performed with Silvaco Atlas were promising, suggesting perfect shallow 10 – 20 nm doping profiles with $>10^{19}$ cm^{-3} activated doping levels at 700 – 800°C diffusion temperatures. Solid antimony oxide film was deposited on silicon surface by ALD by Picosun (PICOSUN™ P-300B batch ALD reactor) from tris(dimethylamido)antimony ($Sb(NMe_2)_3$) and ozone precursors. The film composition was verified by XRD to contain Sb_2O_3 crystallites in amorphous matrix, suggesting amorphous Sb_3O_2 film. The ALD process was optimized on the basis of diffusion and best material was obtained at 200°C deposition with pulse/purge times of 1.6 s/8s for Sb and 1s/4s for ozone. Films of 20 – 100 nm thickness were deposited on crystalline and polycrystalline silicon substrates. Antimony oxide was found to vaporize below 600°C, but it was possible to trap the vapour in the vicinity of the surface by placing it in contact to another wafer. Significant antimony diffusion of was measured from both wafers, but the concentration was much higher and the profile deeper in the original wafer. A layer of silicon rich antimony oxide was formed on the surface of both wafers and was removed by ammonia based etchant. The diffusion in polycrystalline silicon was found to extremely fast, and the concentration of antimony through the 300 nm thick silicon layer was above 10^{20} cm^{-3}. However, only a small increase in conductivity was detected, indicating strong grain boundary diffusion. In crystalline silicon the diffusion profile of antimony was identical to simulations; shallow and high already at 750°C. However, the oxygen concentration in silicon was even higher, making the process unsuitable for doping. Instead of Sb_2O_3, the solid source should be pure antimony as the presence of oxygen on the surface during the antimony diffusion process clearly cannot be allowed.

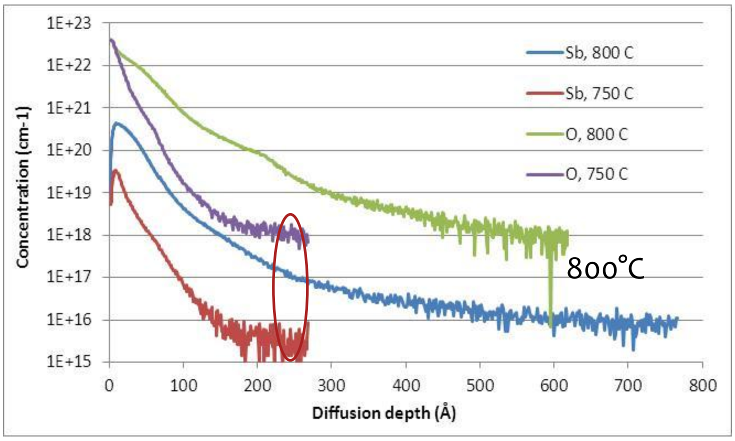


Figure 9 Measured antimony and oxygen diffusion profiles at different drive-in temperatures. Antimony profiles match with simulations, according to which the active surface concentration is always slightly above 10^{19} cm^{-3} even though the total surface concentration increases as a function of temperature. The oxygen concentration is consistently two or three orders of magnitude higher.

<u>Conclusions:</u>

The properties of wires fabricated by different techniques and possibilities to further improve them in view of solar cell applications with radial p-n junctions are summarized in Table 1.

	VLS wires	Wet chemically etched wires
structural properties	low temperature CVD: - max. ~250 nm diameter - no epitaxy on Si substrate when using AuNPs → *high temperature CVD*	- variable structures depending on etching conditions - rough surface - porous wires for higher doping levels → *wires fabricated by nanosphere lithography and wet etching*
optical properties	- samples with small thickness (3 µm) show high absorption at lower wavelength, lower absorption at higher wavelength (diameter dependent)	- depending on degree of order and geometry up to 95 % absorbance over wavelengths 400 – 1100 nm by a thickness of less 5 µm
electrical properties	- possible Au contamination - unknown dopant concentration → *electrical characterization of individual wires*, → *wire growth using Al as a catalyst*	- determined by wafer doping
solar cell fabrication	recrystallization of a-Si:- oxide at the p-n junction (*ex-situ* removal of Au, HF etching), high-temperature process diffusion doping: - removal of residuals → in-situ etching → *gas phase diffusion doping*	
literature results	Gunawan (2009): η = 1.8 %, A = 0.75 cm^2	Garnett (2008): η = 0.46 %, A = 1 cm^2

Table 1: *Properties of wires for solar cell applications fabricated by different techniques and options for further improvement*

WP 6: Contacting Si-NRs by TCO layers from different techniques such as ALD, spray deposition, magnetron sputtering and chemical and electrochemical deposition

WP 6 main objectives were the following:

- Determination of the TCO layer of choice (degenerately doped wide bandgap semiconducting oxides) for the different techniques (ALD, magnetron sputtering, spray pyrolysis, chemical deposition) → ease and calculated price of the process, physical parameters obtainable by the process, scalability of the process;
- development and optimization of TCO layers using these different techniques;
- benchmarking of TCO layers from the different techniques based on properties-conductivity and transparency in the visible;
- concepts for scalability of the processes and price calculations (PICO,BISOL with input from ARC,VTT,EMPA);

Main innovative results:

Prerequisites of the 3D structured solar top contacting differ from the flat solar cell technology by the sound request of conformality required to gain full benefit from the semiconductor 3D structure. Similar to flat solar cell contacting, the TCO top electrode in structured cells must also have high conductivity and transparency whereas issues such as TCO surface microstructure and haze generally required to reduce reflection are relatively irrelevant - unless the TCO film is thick enough to fill the structure and planarize the surface. The properties of the best TCO materials with different methods achieved by the ROD-SOL consortium are summarized in Table 1

***Table 1** Properties of different TCO materials achieved by each method in ROD-SOL. Lower case index in sputtered materials indicates layer thickness in nanometers.*

Method	Layer	Deposition Temp. (°C)	Conformity/ Scalability	Transmission (%) (400-1000nm)	Resistivity (mΩ cm)
ALD (VTT)	AZO (Al_2O_3<5%)	200	excellent/ excellent	87-95	1.4
Sputtering (AIT)	ITO (10% SnO2)	25	medium/ excellent	90-95 (d=100nm)	0.15
Sputtering (AIT)	AZO (2% Al_2O_3)	25	medium/ excellent	85-95 (d=250nm)	1.5
Sputtering (AIT)	$AZO_{50}/Au_x/AZO_{50}$	25	medium/ excellent	(x=5): 75-90 (x=7): 65-90 (x=9): 60-90	(x=5): 0.32 (x=7): 0.18 (x=9): 0.13
Sputtering (AIT)	$AZO_{50}/Cu_5/AZO_{50}$	25	medium/ excellent	(x=5): 65-85	0.30
ECD (EMPA)	AZO	40-80	excellent/ excellent	20-80 (incl. glass+FTO)	Not known
ECD (AIT)	AZO NRs	70	excellent/ excellent	50-90 (incl. AZO)	5

The most commonly used TCO is tin-doped indium oxide (ITO) because of its superior optical and electrical properties. However, the scarcity of indium drives the demand for more abundant materials with similar characteristics. The most promising candidate is doped zinc oxide (ZnO). Despite the fact that there are other TCO's with higher conductivity, ZnO is a stable, abundant material with high light transmittance in the visible. Depending on the deposition method and layer structure, the studied aluminum doped zinc oxide (AZO) materials are very different from the point of view of applicability in structured solar cell contacting.

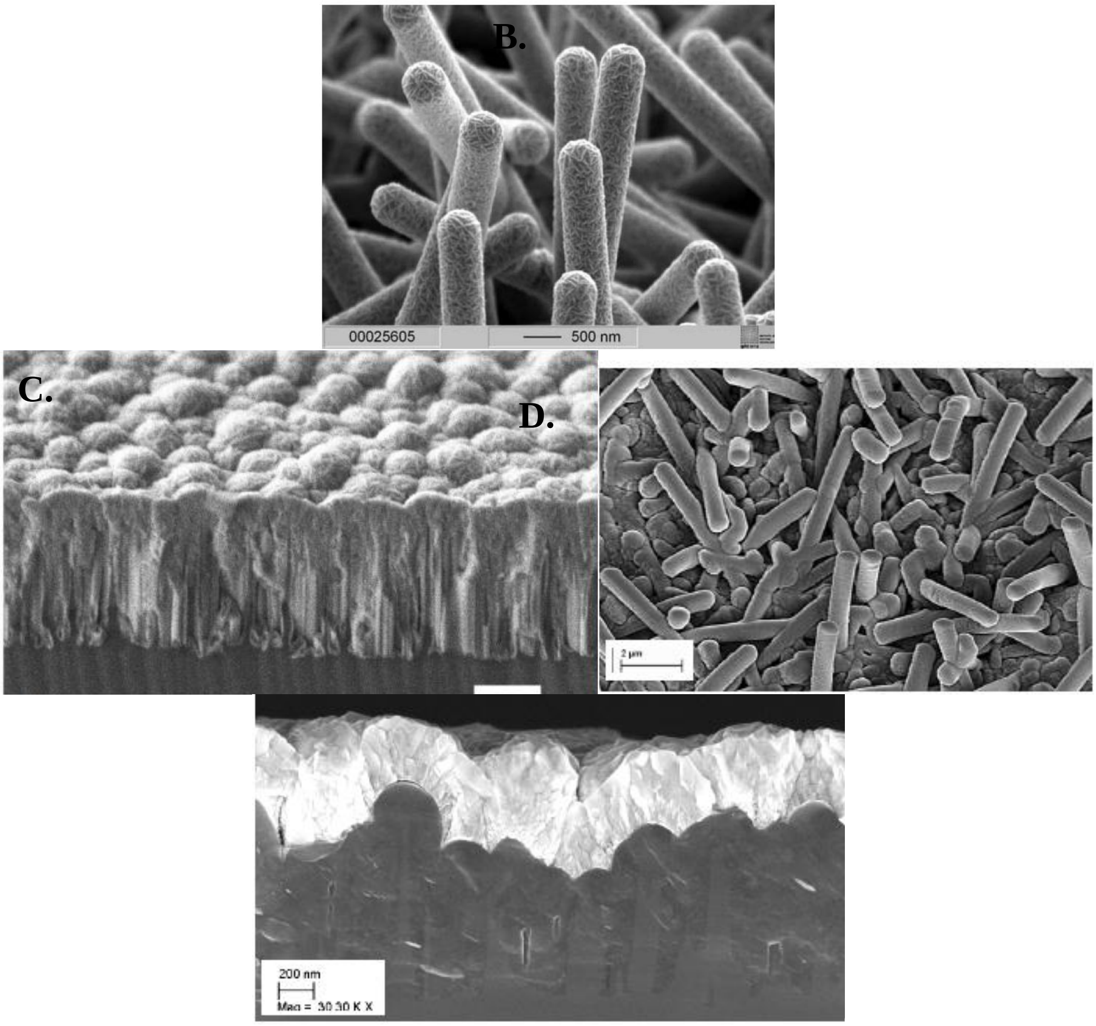


Figure 1 A) Thin conformal ALD AZO on silicon nanowires grown by CVD and B) Thick conformal ALD AZO on etched nanorod ensemble. When ALD film thickness exceeds the nanorod separation, surface morphology changes dramatically. In this case a moth eye like structure is formed. C) Thick (1 µm) sputtered AZO on nanorods and D) a thinner film sputtered on nanorods with polysilicon capping.

High conductivity was obtained with ALD and sputtering as expected, but also with ECD in the case of nanowire type growth the material conductivity was surprisingly high, which is very promising for the future due to the extremely low cost structure of the method.

Highest TCO quality factor, relating the transmission to the conductivity, was achieved by sputtering combinations of AZO with ultra-thin layers of Au and Cu (down to 5nm, as shown in Figure 2) as symmetric AZO/metal/AZO trilayers.[3] For an AZO thickness of approx. 50 nm the optical transmission of the trilayers is maximized. The conductivity and absorption are mainly determined by the thickness of the metallic film. The advantages of these structures are that their roughness is only a fraction of the roughness of the AZO film that would be needed to achieve the same sheet resistance and that their sheet resistance is stable upon thermal treatment in air which is not the case for a stand-alone AZO electrode.[4] Similar trilayers can be also deposited conformally with ALD.

[3] T. Dimopoulos et al., Thin Solid Films **519**(4), 1470 (2010).
[4] T. Dimopoulos et al., submitted to Thin Solid Films

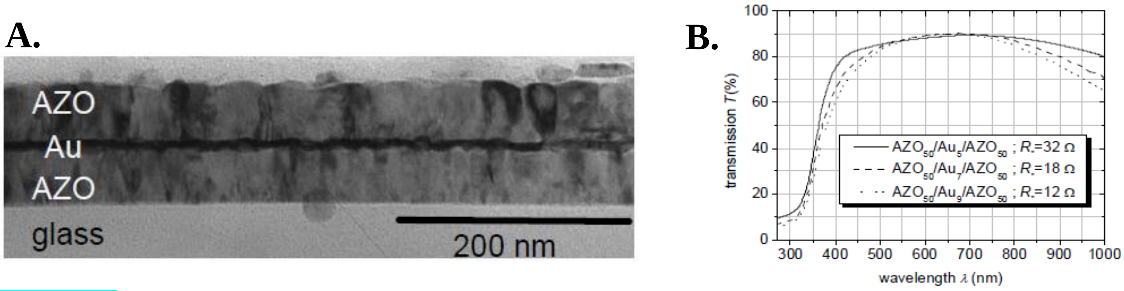
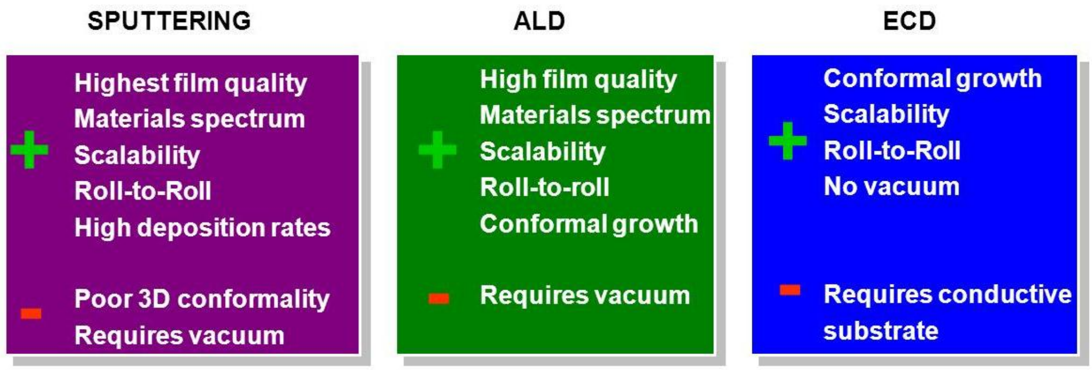


Figure 2 A) TEM image of sputtered AZO/Au trilayer with high transmission and low sheet resistivity. B) Transmission spectra and sheet resistance for trilayers with different Au thicknesses.

Conclusions:

Based on all the information available, it is not evident that one method would be better than others in all applications, even when only considering the nanorod silicon cells, as the strengths and drawbacks of the methods differ as much as the applications.



Sputter deposition is the mainstream method for TCO deposition providing the highest film quality and conductivity. Long competition in the market has provided sputter deposition tools with optimized cost structure and fast operation in solar cell contacting. As far as the requirement for 3D conformality is not too demanding, e.g., in applications based on vertical contacts or structures where the underlying nanostructure is mostly planarized, sputter deposition is therefore favored due to the high throughput and low resistivity. In very low cost applications, where more resistive TCO is acceptable and substrate conductivity is adequate, ECD may also become a viable alternative. In such applications, all methods can provide the required transparency, haze and surface roughness to enhance light trapping.

The most efficient nanorod cells reported this far are the semiconductor/insulator/semiconductor (SIS) cells based on ALD tunnel contacts. ALD is the only possible method for the deposition of the thin conformal Al_2O_3 passivation & tunneling layer with the required precision on 3D structures. For the tunneling contact quality and device performance, it is essential that the TCO is deposited in situ and that the full contact area extending deep into the structure is utilized. Further benefit of ALD is the ability to tune the parameters of the film as a function of distance from the tunnel barrier, thus allowing the optimization of the junction properties like work function or band gap independent of the main conductor properties. In these applications ALD is evidently the method of choice for TCO deposition in the contacts.

However, at least in the case of AZO, thicknesses above 500 nm are recommended to provide necessary stability upon moisture. The full benefit of conformal contact in SIS cells can be achieved by thin conformal TCO, which can be complemented by a thick surface TCO layer sealing the structure and providing lateral conductivity. Thick TCO can, in principle, be deposited with any of the methods investigated. In this situation, the cost efficiency of ALD and sputtering cannot be unambiguously determined without considering the size and full logistics of the production plant. In the case of ECD TCO's, the cost structure is appealing but the physical properties of the novel materials still need to be enhanced – current material quality is not yet adequate for production of high efficiency solar cells, but the development can be fast.

WP7: Structural, electrical, optical and mechanical characterization

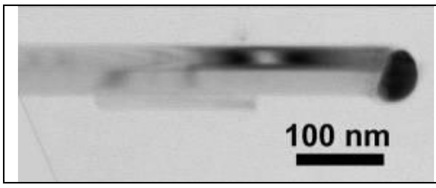
WP 7 main objectives were the following:

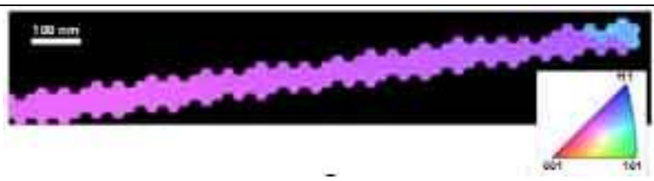
- Determination of NR morphologies
- Determination of electrical properties of individual processed NRs based on in-situ I-V and EBIC measurements in an SEM
- Deriving electrical/solar cell properties of individual processed NRs by extraction of the NR from the ensemble and lithographically contacting and subsequent measuring
- Setup measurement routines of electrical/solar cell properties of processed NR ensembles
- Determination of electrical/solar cell parameters of NR ensembles
- Measurement of optical data for different Si-based NR materials
- Determination of optical data of the InGaN NRs → derive their potential for potential future consideration for solar cell applications
- Determination of electrical and optical properties of TCO layers
- Determination of mechanical properties of individual NRs (bending, tensile testing, etc.) and embedded NRs (pull test, adhesion tests, etc.)

Main innovative results:

VLS grown Si nanorods:

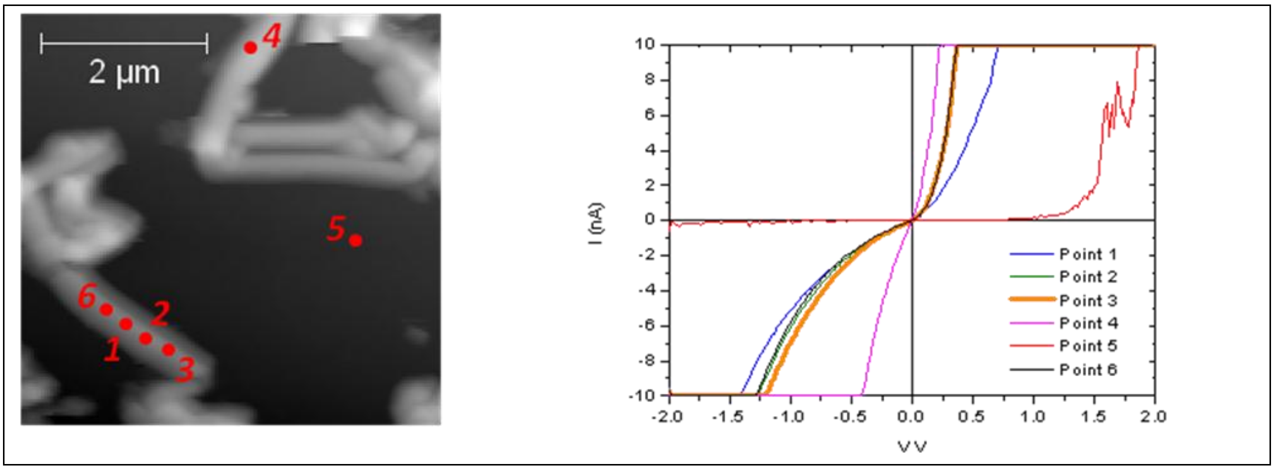
The morphology (kink formation), sidewall quality and crystalline properties were studied by TEM and SEM on nano rods (NRs) formed by Vapor-Liquid-Solid (VLS) technique with gold catalyst. Mostly **straight NRs** were observed, with **domain (twin) boundary** along the NR axis, otherwise the NRs are single crystalline with a smooth sidewall.





EBSD was used to characterize the Si nanowires. An important finding is, that SiNWs grown on Si wafer substrates generally exhibit a **growth direction of <111>** type. However, both EBSD and TEM found, that a part of them are grown along the 211 direction especially, when SiNWs are grown onto glass.

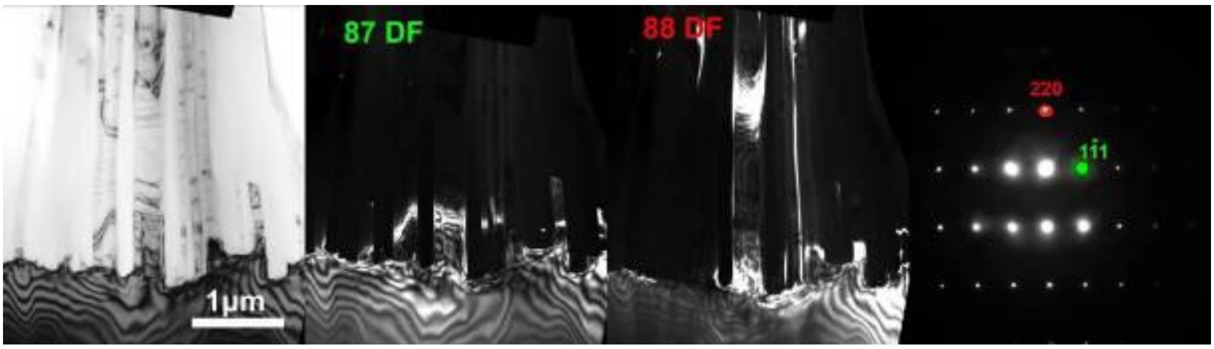
Electrical characterization of individual nanorods has been carried out by Electron Beam Induced Current imaging (EBIC) in order to characterize the pn-junction depth of individual NRs. A nanomanipulator inside a scanning electron microscope was used to bring a conductive AFM tip into contact with NRs. **EBIC** and I-V measurements have been carried out and the presence of the desired **p-n junctions** was verified. Moreover the transport characteristics of Si-NRs by means of conducting AFM (CAFM) were carried out. First, the surface of the sample was scanned in contact-AFM mode and then current-voltage (I-V) characteristics were measured at selected sites of the sample's topography. The next examples are shown on n+(P)-doped Si-NRs grown on a p+(B)-doped substrate.



The obtained I-V curves present rectification that agrees with the diode's doping characteristics.
Another process for contacting individual silicon nanowires based on electron lithography was developed in order to perform electrical characterisation of individual non-degenerate nanowires, which facilitated the direct measurement of the resistivity and analysis of the doping concentration of VLS grown nanowires.
Individual SiNWs were mounted by in situ scanning electron microscopy nanomanipulation, and their tensile properties were determined to demonstrate the device capability. The phosphorus-doped SiNWs, which were grown in a bottom–up manner by the vapor–liquid–solid process, show an average Young's modulus of (170.0 ± 2.4) GPa and a tensile strength of at least 4.2 GPa. Chemically etched SiNWs, with their long axis along the [100] direction, show a fracture strength of 5.4 GPa.

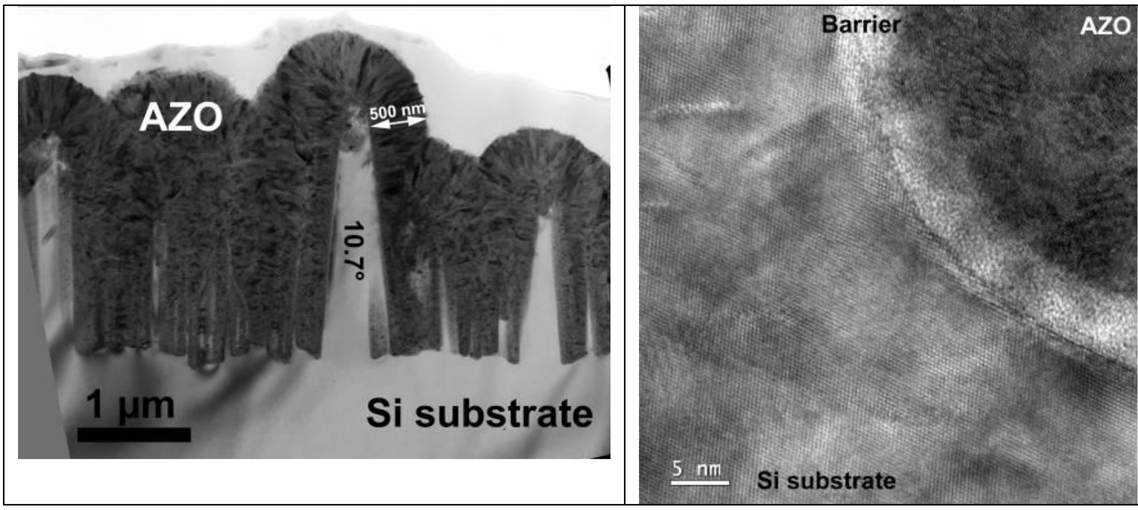
Etched SiNWs:

Following the deposition of Ag catalyst templates NRs were etched in Si wafers. Ag particles catalyzing the etching process practically sank into the Si substrate resulting in a large number of channels. Material remaining between the channels forms NRs. The substrate and the NRs form a single crystalline structure since they natively belong to the same piece of Si single crystal. This was proved by the next TEM images.

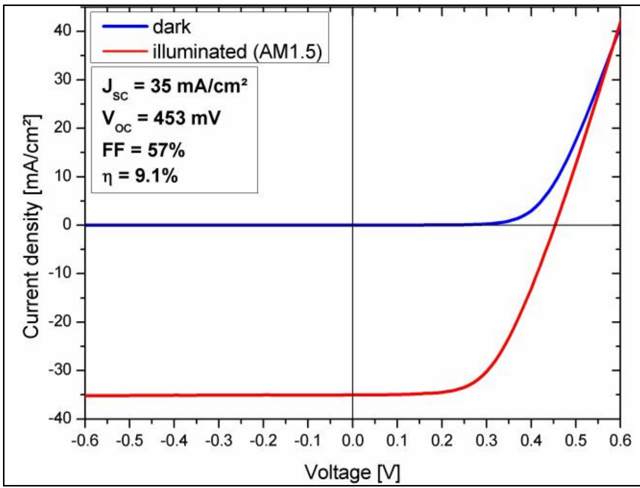


An irregular cross section of the NRs was observed together with a wide size distribution ranging from <100 nm to approximately 1µm on plan view images taken on the NRs.
Silicon nanowire (SiNW) ensembles with vertical and zig-zag architectures have been realized using wet chemical etching of bulk silicon wafers (p-Si(111) and p-Si(100)) with an etching hard mask of silver nanoparticles that are deposited by wet electroless deposition on polystyrene patterned silicon surfaces resulting in a much more **uniform nanowire** "forest" in size. Optical study of those NW ensembles was carried out and additional high energy peaks in room temperature photoluminescence (PL) spectra were observed, mediated by the nanoscale features that are mainly related to two types of origins: (i) surface states or (ii) states related to quantum confinement. A model was set up in order to explain this phenomenon. The most pronounce

explanation for the **strong room temperature light emission** in wet-chemically etched silicon is a quantum confinement effect that originates from the periodically rough SiNW sidewall structures.
Strong antireflection properties have been observed in the SiNWs formed via electroless etching approach.
To understand the influence of an oxide based contact layer around SiNR a thin layer of SiO2 has been deposited around the SiNRs using atomic layer deposition. The thickness of the layer has been determined using TEM micrographs. The optical properties of such **wrapped SiNRs** have been calculated using an extended Mie theory. In the limit of geometrical optics this layer would act as an index matching film and thus reducing the high reflectivity. Since it is essential for thin films built of SiNRs that the light is scattered multiple times to absorb the light this effect has to be overcome. Our results indicate that the optical scattering cross sections of individual SiNRs are not substantially reduced when the diameters are less than 80nm. To experimentally verify the theoretical results spectra of individual wrapped SiNRs have been taken. They are in good agreement with the calculated values.



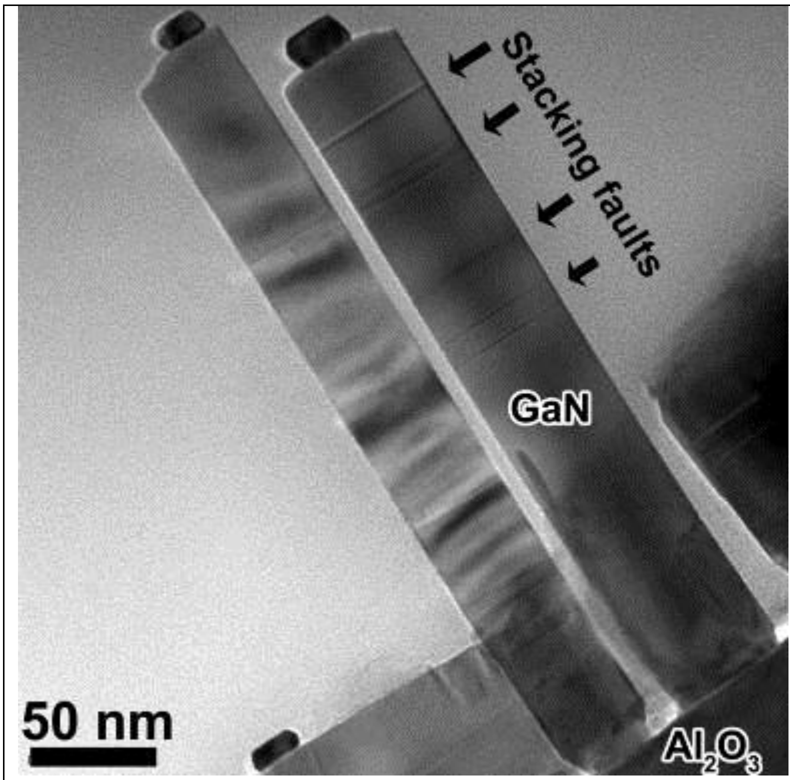
Chemically etched NRs were prepared and coated with an AZO layer deposited by ALD process.
The morphology of the AZO layer and the Si/AZO interface was characterized. The results supported the development of a new solar cell based on the semiconductor-insulator-semiconductor (**SIS**) layer sequence (thin tunnelling oxide (SiO2, Al2O3) with a thickness of 5-20 Å and a thick, transparent conductive oxide (Al doped ZnO) around the silicon nanowires.
The SIS solar cells were characterized electrically as well:



The highest observed open current voltage (VOC, max), short current density (JSC, max) and fill factor (FF) under AM1.5 (1000W/m²) illumination were 470 mV, 37 mA/cm^2 and 67%, respectively at maximum power conversion **efficiency of 9 %.** On the left side the J-V curve of the record cell and its electrical parameters are shown.

TCO layers: Transparent conductive materials of different types were grown, in some cases a thin metal layer was sandwiched between the two TCO layers. Beside the structural characterization the electrical parameters were also measured and the resistivity of the TCO layers decreased.

GaN nanorods:



The samples were grown by MOCVD using small gold catalyst particles. First a thin gold film was evaporated onto sapphire and small gold grains were prepared by annealing that before the MOCVD growth. The nitride growth was carried out in an AIXTRON reactor at the temperature of 950°C from TEG and ammonia precursors.

Transmission electron microscopy revealed long (about 500 nm) and thin (about 50 nm) rod of hexagonal GaN with a gold grain on the tip of that (see the image on left). The diameter of the gold grain is about 20 nm and it shows facets on the surface. In some of the nanorods stacking faults were observed and investigated in high resolution.

Epitaxial growth of GaN on sapphire under gold catalyst was confirmed. GaN was grown in each case 0002 oriented.

Optical characterization shows only near band edge emission and **no yellow defect band** luminescence is visible in GaN nanorods grown catalyst-free. This is pointing out the high optical quality of the catalyst-free grown GaN NR structures in comparison to the VLS grown GaN NWs. For InGaN quantum wells grown around the GaN nanorods lower growth temperature is suggested based on the optical measurements.

Due to their small aspect ratio of GaN NRs grown by MOVPE, tensile testing of the NRs is not possible. Instead, the mechanical properties have been evaluated in an SEM in situ micro-compression setup. At room temperature, the GaN structures showed a yield strength of about 7 GPa and subsequent **plastic deformation**. In macroscopic GaN structures, no plasticity is observed at room temperature and the material has a brittle behaviour. The plasticity in the GaN NRs is due to a size effect and could be beneficial for applications in PV systems.

Conclusions:

WP7 carried out detailed structural, mechanical, optical and elelctrical characterization of nanorods. Some of the characterization methods developed for testing very thin wires can be used more generally for the characterisation of nanowires. The systematic feedback to the growth of nanowires resulted in useful device structures with improved properties.

WP 8: Test and model device structures: extraction of solar cell parameters

Report on optical modeling:

1) Optical modeling could give an answer on the optimal organization of the nanorod ensembles and also on the optimal location of the p-n junction within the nanorods. In order to get some insight into the absorption profiles, we used optical simulator FEMOS 2D [1]. This numerical simulator uses the finite element method (FEM) to solve Maxwell equations. The input parameter is a two-dimensional wavelength dependent complex refractive index N, comprised of the real part n – the refractive coefficient, and the complex part k – the extinction coefficient. The input solar spectrum used in simulations is AM1.5g ranging from 400nm to 1100 nm, which is the preferred absorption range in solar cells. From the incident TE and TM waves, the spatial distribution of electric and magnetic field is calculated in the incident direction: E_z and H_z respectively, where z is the direction of incident wave.

We have compared following structures to get some insight into the wave interference effects and the wavelength-dependent reflectance properties of the nanorod structures:

a) Flat structure air/c-Si with no nanorods.
b) Structure air/c-Si with 2 µm long and 2 µm wide, periodically distributed nanorods.
c) Structure air/c-Si with 20 µm long and 2 µm wide, periodically distributed nanorods.
d) Structure air/c-Si with 2 µm long and 200 nm wide, periodically distributed nanorods.

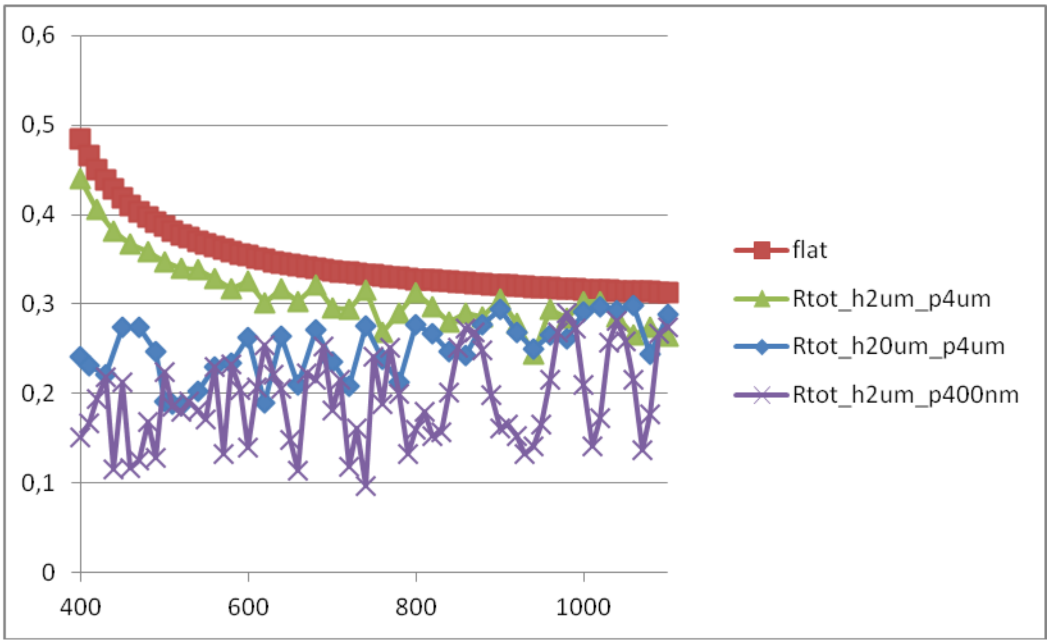


Figure 1: Comparison of the wavelength-dependent reflection of the flat Si surface and the periodically distributed nanorods on the Si surface. The nanorods are 2µm or 20µm long, and have the diameter equal to 2µm or 200nm. The legend denotes period which equals two times the diameter of the nanorod.

A decreasing reflection with the increasing nanorod length can be observed, keeping the period of the nanorod ensemble fixed to 4µm, blue and green curves in Fig. 1. Longer nanorods behave as a waveguide, leading the wave deep into the nanorod well (Fig. 2 – B1), allowing it being absorbed also in the side walls. This antireflection effect is less pronounced in longer wavelengths – above 900 nm, which can be explained by deeper penetration of longer wavelengths.

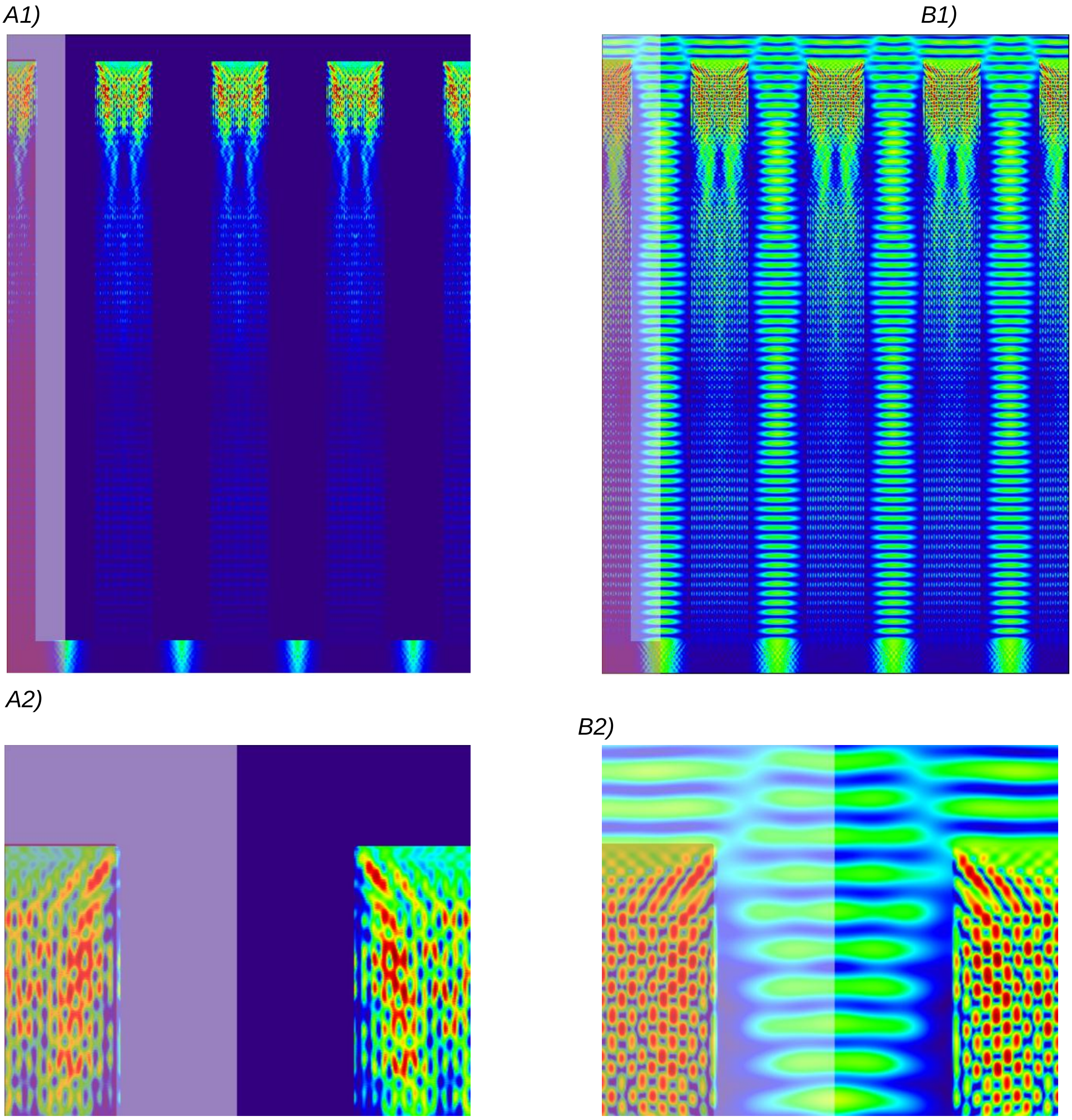
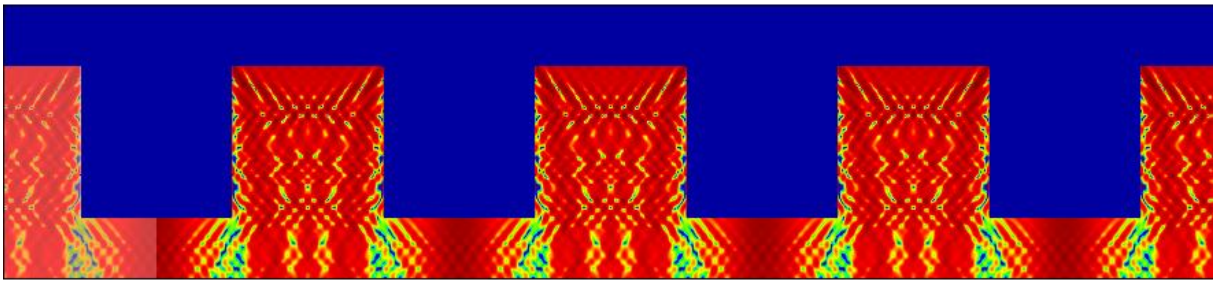


Figure 2: Absorption and transversal electrical field - E_{xy} distributions in 20 µm long and 2 µm wide periodically distributed nanorods. Distributions are calculated for 640 nm incident TE wave. A1 shows the absorption distribution, A2 depicts the detail at the top of the nanorod, where the absorption is the most significant. B1 and B2 correspondingly show the E_{xy}.

From Fig. 2 – A1 we can see that the most of the incident absorption at 640 nm occurs in the top 10 µm of the nanorod ensemble. In flat silicon a significantly longer absorption distance is needed to gain similar absorption. Although the difference in the reflection at 640 nm between the 2 µm and 20 µm long nanorod ensembles equals 10% - Fig. 1, in 2 µm long nanorods, a significant portion of the incident wave will penetrate the nanorod ensemble and continue its absorption in the bulk silicon, as shown in Fig. 3.

A1)



A2)

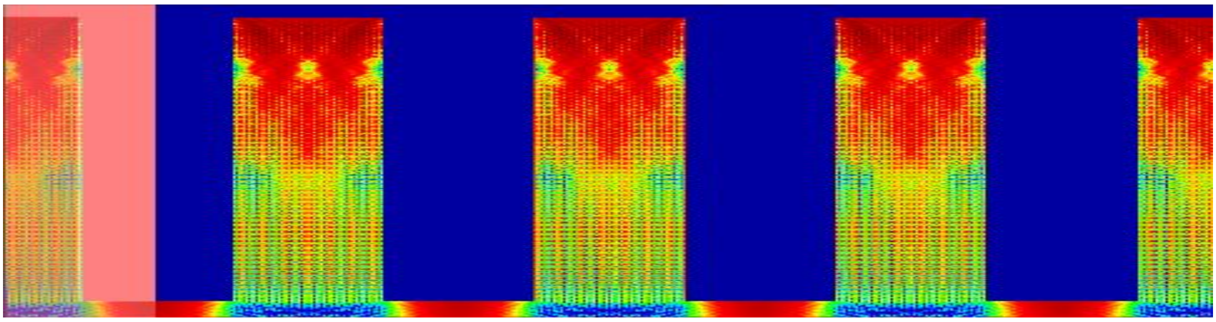
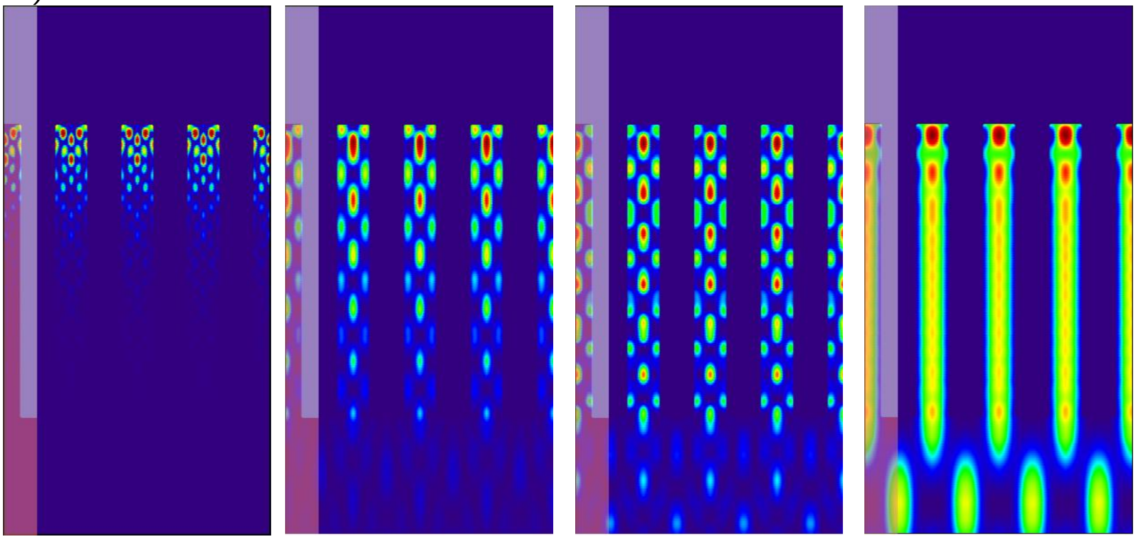


Figure 3: Comparison of absorption profiles in decade-logarithmic scale: blue areas equals to 0.001, dark-red to 1. A1 shows the 2 µm long nanorods in scale with the period, while the vertical scale of 20 µm nanordos equals 1:5 – A2. The absorption profiles are calculated for 640 nm incident TE wave.

A comparison of the absorption profiles of Fig. 3 can set a basic rule for designing the electrical structure of the nanorod solar cell. In the case of 2 µm long nanorods with the period of 4 µm (case A1), it could be speculated that the SIS configuration would be preferred. A significant absorption occurs in the top and at the bottom of the nanorod, therefore the surface should be well passivized and strong repellent field should be present at the oxide-silicon heterointerface. The p-n junction should be located deeper in the structure. This type of solar cell could resemble crystalline silicon solar cell, where the nanorod ensemble would work as the antireflection surface. In the case of 20 µm long nanords with the period of 4 µm (case A2), most of the incident light absorbs in the top 10 µm. Since the light absorption in majority occurs in the axial direction, the axial type of p-n junction within the top 10 µm could result in optimal solar cells. However there is still evident a significant absorption at the root of the nanorods (bottom of the well), therefore for an enhanced absorption a change of period could be favorable.

Making the nanorods thinner and thus decreasing their period, one can also observe a decreased reflectance in the longer wavelength region, Fig. 1. However the interference effect significantly develops, but in reality due to geometrical imperfections this would probably be blurred into a smooth effective reflection below 20%. From Fig. 4 we can observe that the absorption occurs throughout the complete nanorod ensemble in whole AM1.5g wavelength range. In wavelength region above 640 nm also a significant light penetration occurs, exhibiting excessive generation in the bulk region.

A1)



A2)

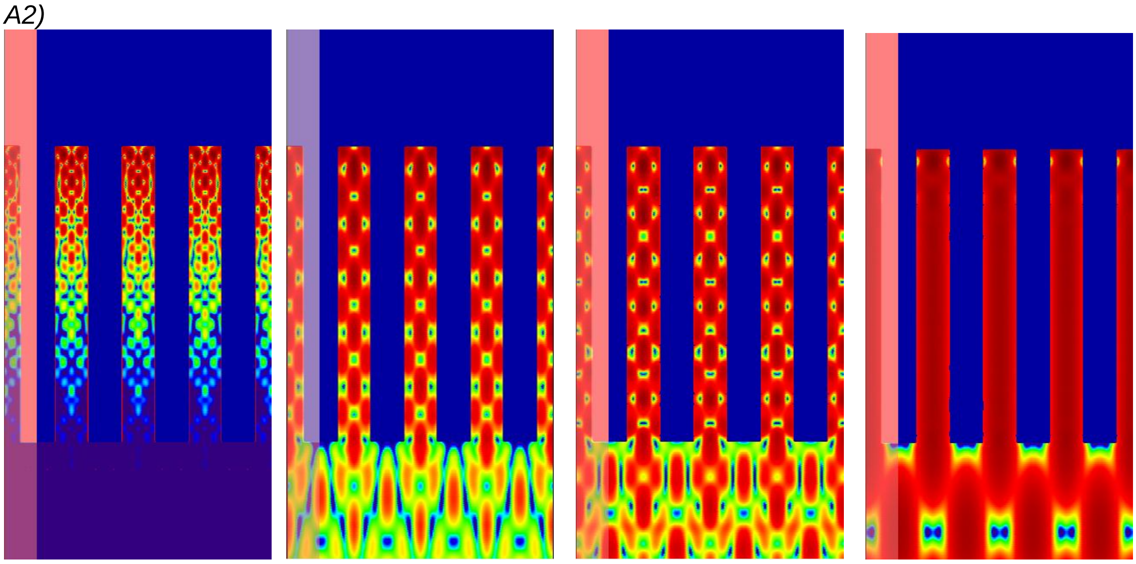


Figure 4: The absorption distribution in 2 µm long and 200 nm wide nanorod ensembles at 450nm, 550nm, 640nm and 850nm, going from left to right respectively. A1 series shows the linear scale, A2 series shows the decade-logarithmic scale: blue areas equals to 0.001, dark-red to 1. Length and the period of the ensembles are not in scale.

Optical simulations of the nanorod ensembles replicate etched structures that clearly show the antireflection effect as a consequence of the interference properties of the ensembles. From the optical simulations we have learnt that these can be used to optimize the length and the diameter of the nanorods. We can observe that the absorption in the radial direction has ambiguous wavelength dependent nature, and therefore cannot be used as a measure to position the radial p-n junction. In all modeled cases of the nanorod ensembles, we can observe the antireflection effect. However from the logarithmic scales, a significant absorption may also be seen in the silicon bulk region. Therefore further optimization should be conducted on the optimal diameter and period of the nanorods, where the optimization criterion should be minimization of reflectance and maximization of the bulk absorption.

References:

[1] CAMPA, Andrej, KRC, Janez, TOPIC, Marko. Two-dimensional optical model for simulating periodic optical structures in thin-film solar cells = Dvo-dimenzionalni opticni model za simulacijo periodicnih opticnih struktur v tankoplastnih soncnih celicah. Inf. MIDEM, mar. 2008, letn. 38, st. 1, str. 5-10, ilustr. [COBISS.SI-ID 6801492].

Report on solar cell parameters measurements:

Solar cell parameters of the nanorod SIS solar cell sample, made by the IPHT, were measured with the following laboratory equipment: Oriel class A solar simulator [1], Keithley 238SMU ampere-meter [2], Lambda 950 spectrometer [3], and with the professional in-line solar cell tester machine from the manufacturer NPC [4]. The laboratory services were kindly provided by the staff of the Laboratory of Photovoltaics and Optoelectronics, Faculty of the Electrical Engineering, Ljubljana University. The professional in-line solar cell tester machine is one of two class AAA solar simulators of the Bisol's production facility.

Fig. 1 shows the *I-V* characteristics measured with the laboratory equipment. The short-circuit current I_{sc} equals to 19,4 mA, the open-circuit voltage V_{oc} equals to 0,458 V, and the fill-factor *FF* equals to 67,6%. The solar cell's AM1,5g conversion efficiency η equals to 4,17%, where the surface *A* of the solar cell's sample equals to 1,44 cm^2. Taking into account the shaded area of 17,6 mm^2 of the contact grid, and subtracting it from the total solar cell area, the effective conversion efficiency increases to 4,75%.

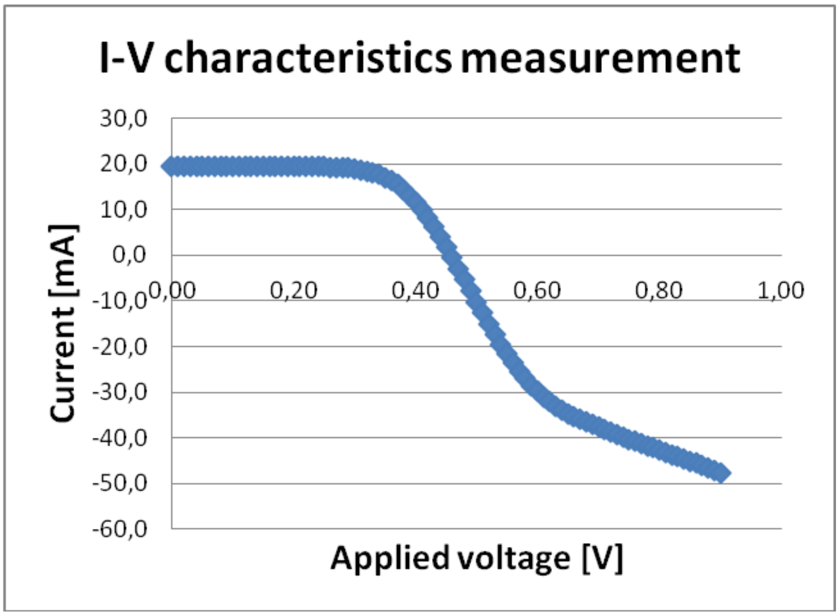


Figure 1: *I-V* characteristics of the SIS solar cell measured in the laboratory environment using Keithley 238SMU current meter and the A-class solar simulator equipped with the AM1.5 filter. The effective conversion efficiency equals to 4,75%.

The SIS solar cell was also measured with the in-line solar cell testing machine of the producer NPC. The measurement setup is shown in Fig. 2. Because the dimensions of the SIS solar cell sample are significantly smaller (12mm x 12 mm) comparing to the standard c-Si solar cell (156mm x 156 mm), an additional measurement platform had to be made in order to mimic the front and the back contacts. Fig. 3 shows the qualitative comparison of the measured characteristics. The NPC solar cell tester does not allow exporting of the whole *I-V* characteristics, but only gives the measured parameters: the short-circuit current I_{sc} which equals to 21,8 mA, and the open-circuit voltage V_{oc} which equals to 0,453 V. *FF* and η were not calculated, most probably due to the J_{sc} values that are not common to c-Si solar cells.

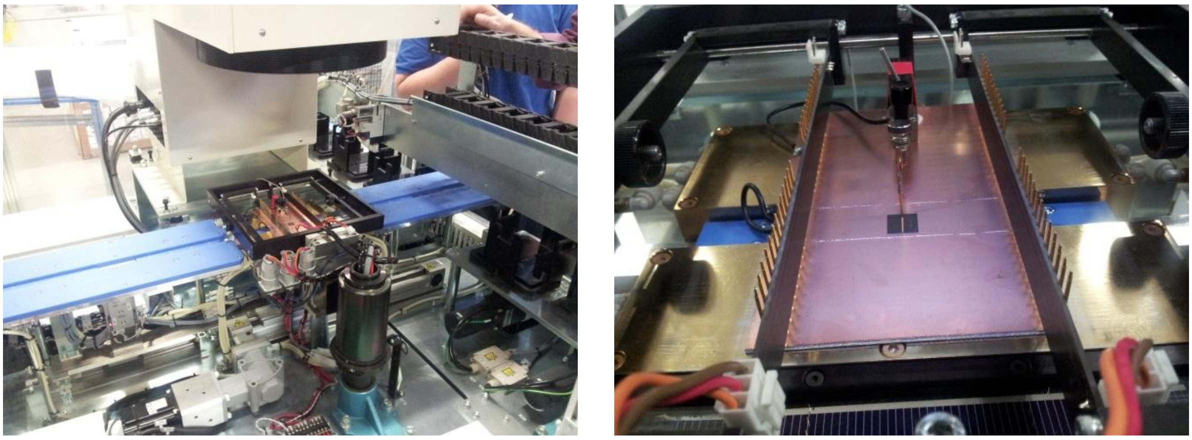


Figure 2: Measurement setup for the SIS solar cell sample to be measured with the in-line solar cell testing machine.

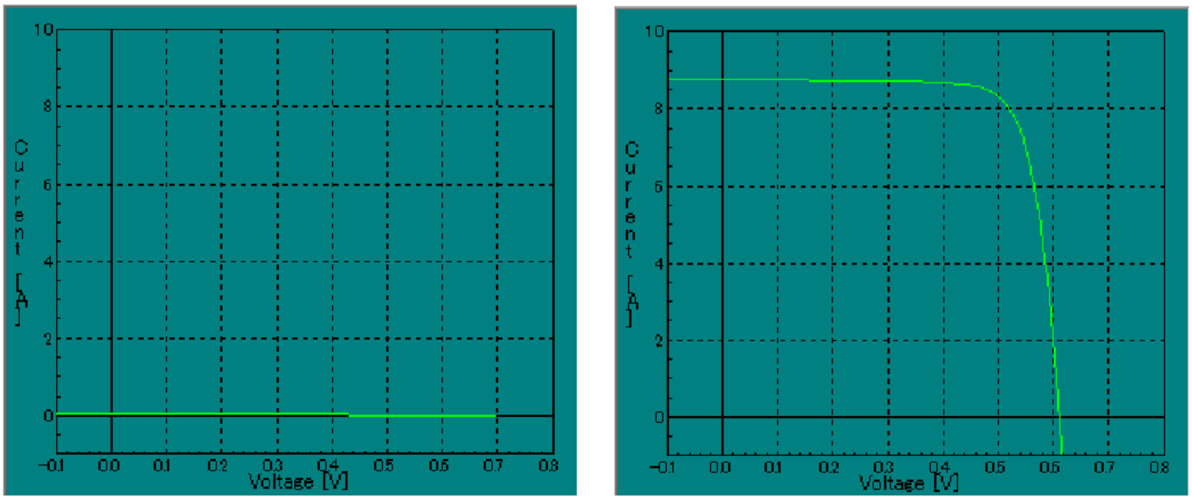


Figure 3: *I-V* characteristics results comparison of the SIS solar cells sample (12mm x 12mm) and of the state-of-the-art c-Si solar cell (156mm x 156mm) measured with the in-line solar cell testing machine. The characteristics show the absolute measured values of current in Amperes.

The characteristics in Fig. 3 cannot be directly compared, since they show absolute values of current, and not the current density. For more fair comparison, we recalculated the currents into the current densities. We could only digitize the measured *I-V* characteristic of the c-Si solar cell from the taken snap shot. The SIS characteristic could not be exported (not supported by NPC) nor digitized form the snap shot (the scale did not adapt) therefore we used the characteristics as measured with the laboratory equipment (Fig. 1). The comparison of the *J-V* characteristics of the c-Si solar cell as measured with the in-line tester and the SIS solar cell as measured with the laboratory equipment is shown in Fig. 4.

By comparing the output parameters one can observe that in further development of the SIS solar cell main improvements should be made on the short-circuit current density and the open-circuit voltage. These two parameters are closely related if the collection properties of the solar cell are poor as indicated by *FF*. That would mean that improvement of the *p/n* junction would similarly result in the improvement of the V_{oc} and J_{sc}. However in this case the *FF* of the SIS solar cell is of fair quality equal to 67,6%, and leading us to a conclusion that SIS solar cell has good collection properties and good electrical structure of the *SIS* junction. In order to get better insight into the collection properties we compared the absorption and the external quantum efficiency *EQE,* Fig. 5. The absorption does not exactly represent the absorption in the SIS solar cell, but rather the total incident flux lowered for the reflected light. But because the back contact of the SIS solar cell is completely opaque, the non-reflected light is either absorbed in the SIS solar cell and/or in the silver back contact.

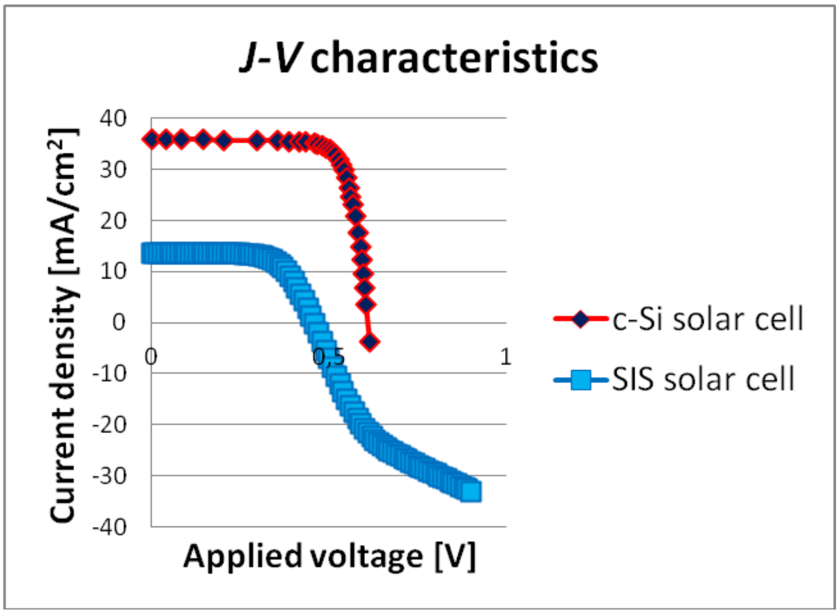


Figure 4: *J-V* characteristics of the c-Si state-of-the art solar cell and the SIS solar cell. Parameters of the c-Si solar cell are: J_{sc} = 34,8 mA/cm^2, V_{oc} = 0,612 V, *FF* = 78,6%, and the η = 16,7%. Parameters of the SIS solar cell are: J_{sc} = 13,5 mA/cm^2, V_{oc} = 0,458 V, *FF* = 67,6%, and the η = 4,17% (4,75%) The SIS *J-V* tail ranging from 0,6 V to 0,9 V indicates a non-ideal back contact.

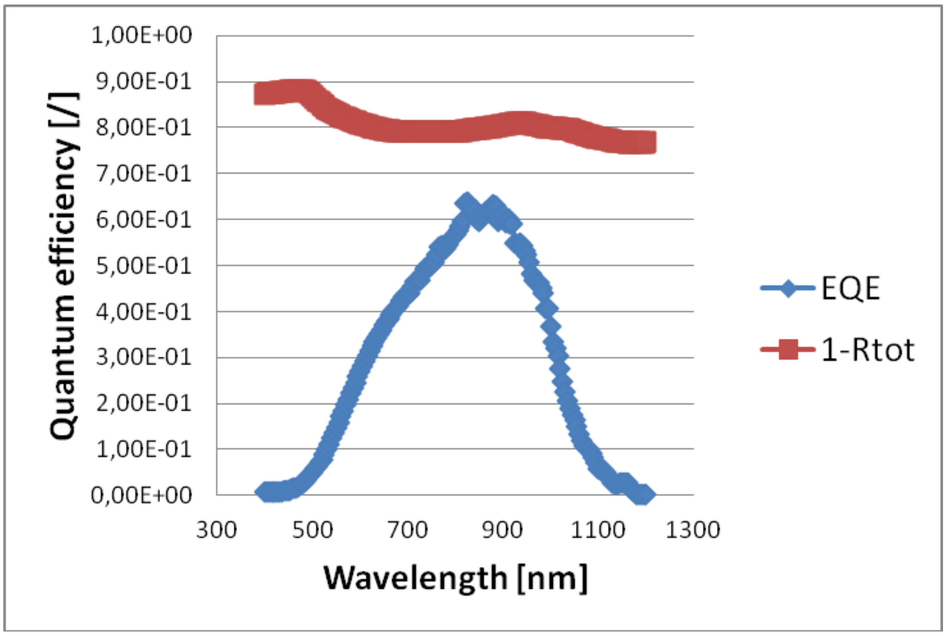


Figure 5: Comparison of the absorbed photon flux 1-R_{tot}, where R_{tot} is a total reflection, and the external quantum efficiency *EQE*. The *EQE* describes the ratio between the extracted electron-hole pairs and the incident photons.

The difference between the 1-R_{tot} and the *EQE* curves therefore comprises of the generated, but not collected carriers, i.e. recombined carriers, and of the photon flux that did not contribute to carrier generation, but was rather absorbed in the back contact. Since the *EQE* shape from 900 nm

to 1200 nm represents a characteristic band-gap cut-off of the absorption, we assume that the *EQE* maximum at 900 nm to large extent represents the absorbed photon flux, and less recombination losses. Therefore the difference to the 1-R_{tot} at 900 nm could to a large extend be attributed to the photon flux which was absorbed in the back contact. Part of this loss could also be attributed to the back contact recombination, especially since the *J-V* curve of the SIS solar cell (Fig. 4) indicates a non-ideal and therefore an electrically non-repelling back contact.
A significant loss of the generated carriers may be observed in the low and the middle wavelength region of the absorbed spectra. These losses can be attributed to the non-ideal position of the *SIS* junction, where the top *Al:ZnO* layer might be too thick, absorbing a large portion of the low-wavelength photons.

We can conclude that for an improvement of the SIS solar cell efficiency following steps could be beneficial:

- To improve the J_{sc}: a thicker absorber region (higher nanorods) and/or better back contact optical reflector should be used.
- To improve the V_{oc}: a back contact surface field that would repel holes and lower the recombination losses.
- To improve both J_{sc} and V_{oc}: a thinner top *TCO* layer should be made.

References:

[1] http://www.newport.com/

[2] http://www.keithley.com/

[3] http://www.perkinelmer.com/

[4] http://www.npcgroup.net/

WP9: Dissemination, benchmarking, exploitation and standardization

WP9 main objectives were the following:

- Planning optimization of industrial CVD reactor for NR-based solar cell production
- Planning optimization of industrial ALD reactor for TCO deposition on NRs for a thin film solar cell concept
- Summary of technology watch and comparison of ROD_SOL material, concepts, achievements to achievements with other thin film concepts
- Moreover, this work package aims at implementation of dissemination and exploitation strategies adapted to the specificities of the ROD_SOL project/consortium

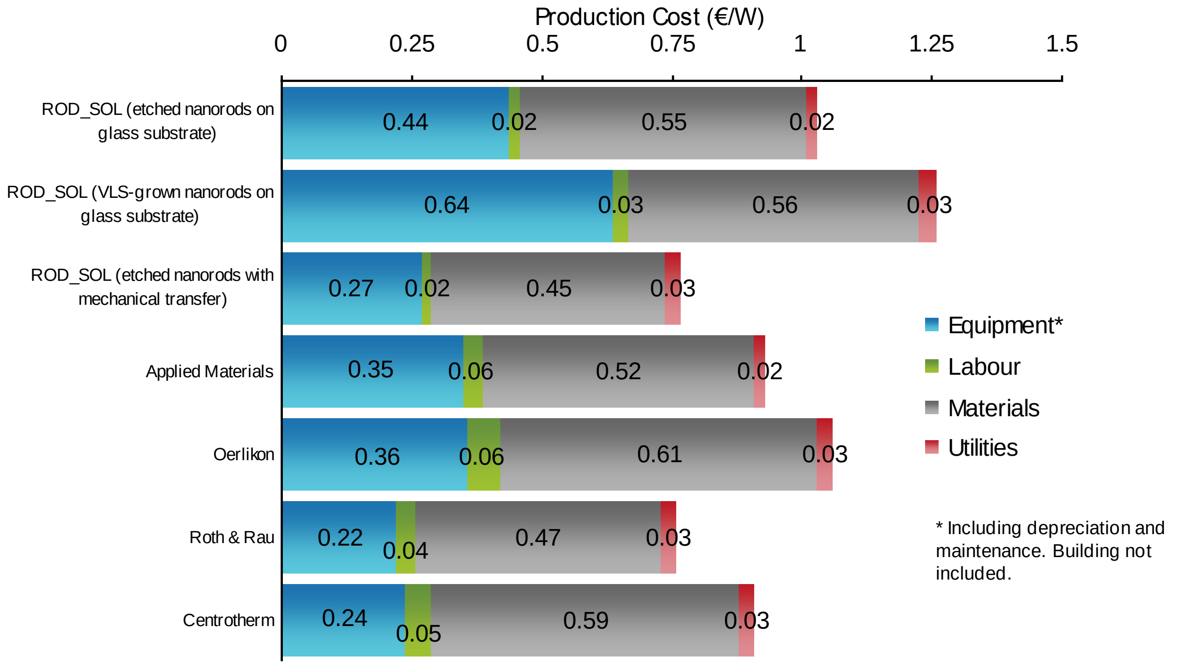
Main innovative results:

- To benchmark the ROD_SOL approach against state-of-the-art technologies the major thin film production processes and the available turnkey solutions have been analysed.
- A tool has been developed and implemented that allows to model the respective production costs in a bottom-up approach.
- Three ROD_SOL approaches that are the most relevant ones with regard to a commercial exploitation of the technology were identified:

- Etched nanorods on glass substrate
- Nanorods grown through the vapour-liquid-solid (VLS) process on glass substrate
- Etched nanorods on monocrystalline silicon wafers with subsequent transfer to glass substrate

- The cost structure of the three relevant ROD_SOL approaches were modelled in detail for a laboratory-scale process and a hypothetical industry-scale process. The calculations were based on two major assumptions:
  - ROD_SOL manufacturing processes can be scaled to industrial volumes
  - A conversion efficiency of 15% is achieved on module level

Figure 01: Comparison of production costs of ROD_SOL (industry-scale) and commercial thin film turnkey lines



<u>Conclusions:</u>

- An assessment of the cost structure of ROD_SOL was provided.
- For industrial manufacturing volumes the calculated costs are comparable to those of current commercial thin film lines.
- Considering the early stage of the ROD_SOL technology these results suggest that the ROD_SOL approach bears some commercial potential.
- In view of the technological uncertainties that are involved with ROD_SOL at this point and the extreme cost pressure that is currently reshaping the photovoltaic industry the challenges for a successful implementation appear tremendous.

WP10: Management

This work package aimed at implementing a Project management adapted to the specificities of the ROD_SOL project and to animate the Consortium. To ensure an efficient project management, the consortium relied on IPHT, being professional and experienced in European Projects Management, based on having respective administration in place that was in charge of the operational day-to-day management allowing the partners to focus on the technical tasks.

It covered the subsequent tasks:

Task 10.1 Financial aspects (IPHT)

Task 10.2 Technical reporting (IPHT)

Task 10.3 Day-to-day follow-up (IPHT)

Task 10.4 Project identity definition (IPHT)

IV. ROD_SOL Milestones

The following milestones have been successfully reached by the ROD-SOL project:

MS1	Metal templates for the different CVD processes and substrates glass / Si wafer optimized; Decision made of patterning needed, which metal, which thickness
MS2	Receipts for different CVD processes established for high quality NR growth of different NR diameters and ensembles for glass/Si substrates
MS3	Chemically etched NRs available delivered to the characterization and TCO and doping initiatives to establish their measurement and growth techniques
MS4	Numerical simulations of NR based solar cells available based on which process and device optimization becomes feasible
MS5	I-V-measurements of processed NR ensembles for extraction of solar cell parameters established
MS6	I-V- and EBIC measurements of processed individual NRs in situ in an SEM established
MS7	Receipts for axial and radial p- and n-doping from different techniques derived
MS8	Embedding procedures for NRs for planar, 3D devices and for the depilation processes developed
MS9	Scalability strategies for the novel NR-based solar cell material determined and production costs estimated (price per Watt peak)
MS10	Experimentally achieved and achievable (with the NR based thin film concept) efficiencies, FF, Voc and Isc measured, estimated and calculated, available
MS11	Fab track reactor concepts for industrial CVD processes and ALD TCO or other TCO processes laid out
MS12	Technology watch accomplished for the time of ROD_SOL and predictions for the development of thin-film solar cells in the future
MS13	ROD_SOL’s exploitation strategy elaborated and exploitation to date documented
MS14	Consortium Agreement signed, Delivery of Management Tools during project Kick-Off

V. Potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

However, among various sources of energy, sunlight is the most abundant and cleanest natural energy resource. In principle, photovoltaics (PVs) hold a great promise to exploit the sunlight to generate clean energy to accommodate the ever-increasing energy demands. Photovoltaic (PV) is the field of technology and research related to the application of solar cells for energy generation by converting solar energy directly into electricity. Solar cells are particularly useful as power generators in distant and terrestrial places like weather stations and satellites. Solar cells are used in small devices like watches and calculators, but mostly they are used to produce electricity either in large-scale power plants or by being incorporated into walls and rooftops. The function of solar cells essentially involves the presence of a p-n junction close to its surface in order to create potential difference in the bulk. About 90% of solar photovoltaic modules are silicon-based, but in recent years increased demand for silicon solar cells has inflated the price of solar-grade silicon. The price of Si accounts for about half of the price of solar cells. The grid parity of electricity produced by solar cells is close to 1 USD/Watt assuming a 20-year lifetime of the cells, but the price is currently four times higher.

One obvious way to **lower the cost** is to reduce the amount of silicon in the cells. By using thin-film technology, the thickness of the silicon can be reduced from 200 μm to 0.2–5 μm. Another way to cut down production cost is to use low-grade Si instead of ultra-pure Si currently being used. However, this lower-grade material is less efficient. It is presumed that the grid parity of solar cells will be reached by using thin-film technology or a new design that is most-likely based on nanotechnology.

Rod-Sol project is unique as it involves partnerships/cooperation across disciplines from fabrication of nanostructures (chemist/material scientist), thin-films technology (device engineer) to a large range of advanced analytical material science methods (physicist/engineer/material scientist). The silicon based approaches are certainly favored because of material abundance and non-toxicity at a high level of materials control and understanding together with a **huge industrial infrastructure** to account for **low production/processing costs** and **high production yields**. For all device concepts based on nanostructures, the crystal structure, geometry, interfacial properties between the SiNW and the substrate as well as the Si core and the shell of the SiNW, dopant concentrations and impurity levels are of **key importance** for functioning of the devices. VLS approach gives **high-quality** NWs but requires the use of hazardous silane gases at high temperature and metal catalyst.

Alternatively, catalyst free SiNWs can be realized by electroless wet chemical etching or electrochemical etching into bulk Si wafers or even thin silicon layers (they can be single-, multi-, nano-crystalline or even amorphous) on substrates such as glass as was developed and investigated during Rod-Sol project. Engineering flexibility in doping characters of silicon nanowires is highly desirable to widen the range of their potential applications. Metal-assisted wet chemical etching (MAWCE) is a simple and low-cost approach to fabricate SiNWs with designable doping nature. In MAWCE, SiNWs are fabricated through (non)uniform etching on silicon substrates in aqueous acid solutions, which is catalyzed by electroless deposition of metal nanoparticles on the substrate surface.

The knowledge acquired from this “Rod-Sol” project regarding the synthesis, processing, optimization and characterization of silicon nanostructures which can be used to form the

fundamental basis for the design and construction of **efficient, cost-effective energy-harvesting** device production lines.

This project has also involved exploratory work on surface treatment of SiNWs to address the limiting issue of **high energy conversation** degrees and testing of different surfaces for the **low cost production**. During Rod-Sol project the **new type of photovoltaic architecture** based on non-typical p-n junction was developed. The **novelty of depositing transparent** conductive oxide and barrier layers lies in the fact that unlike the ALD approach they can be used to simultaneously, in one step, passivate and embed in a matrix the SiNWs which is **essential for "real life" solar cell devices.**

The **anticipated benefit from this project** is firstly the **new knowledge** gained from these **innovative nanostructures** which will be invaluable both from **a fundamental point of view** and for the **near future development** of **new advanced energy technologies**. The highest open-circuit voltage under AM 1.5 illumination was 470 mV. Under these conditions a short-circuit current density of 35 mA/cm^2 was measured. The highest power conversion efficiency of SiNWs based SIS solar cell was over 9 % which shows potential for low cost (<1.0 $/Wp) solar cells with such a design.

The **most promising and important factor is the improvement of the** Voc which can be tuned by the SiNW dominated surface structure. We see a real potential for further improvement of solar cell parameters such as Voc to 600-700 mV and a power conversation efficiency of >15% as a main objective of this project – "from laboratory to industrial scale". The transfer of SIS concept on R2R production line can give the following global exceptional advantages like: (i) reducing of silicon consumption; (ii) reducing of total PV module weight; (iii) reducing of building static costs; (iv) reducing of CO_2 emissions during the production process.

European project ROD_SOL: List of participants

<table>
<tr><th>No.</th><th>Participant name</th><th>Short name</th><th>Country</th><th>Type</th></tr>
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Co: Coordinator, Cr: Contractor

Address of the project public website: **www.rodsol.eu**

Project logo:

Grant Agreement number: 227497

Project acronym: **ROD_SOL**

Project title: **All-inorganic nano-rod based thin-film solarcells**

Name of the scientific representative of the project's co-ordinator[5], Title and Organisation:

Dr. Silke H. Christiansen, IPHT – Institute of Photonic Technology

[5] Usually the contact person of the coordinator as specified in Art. 8.1. of the grant agreement

VI. Use and dissemination of foreground

Section A (public)

TEMPLATE A: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[6] (if available)	Is/Will open access[7] provided to this publication?
1	Synthesis Mechanisms of Organized Gold Nanoparticles: Influence of Annealing Temperature and Atmosphere	Mikhael Bechelany	Crystal Growth & Design	Vol. 10, No. 2, 2010	ACS Publications	Washington	2010	p. 587–596.	http://pubs.acs.org/doi/abs/10.1021/cg900981q	no
2	Silver Coated Platinum Core-Shell Nanostructures on Etched Si Nanowires: Atomic Layer Deposition (ALD) Processing and Application in Surface Enhanced Raman Spectroscopy	Vladimir A. Sivakov	ChemPhysChem	Vol. 11(9), (2010)	Wiley	Weinheim	2010	1995-2000	www.mpi-halle.mpg.de/mpi/publi/pdf/9627_10.pdf	yes

[6] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).
[7] Open Access is defined as free of charge access for anyone via the internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

3	Realization of Vertical and Zigzag Single Crystalline Silicon Nanowire Architectures	V. A. Sivakov	J. Phys. Chem. C	2010, 114	ACS Publications	Washington	2010	3798–3803	http://pubs.acs.org/doi/abs/10.1021/jp909946x	no
4	Roughness of silicon nanowire sidewalls and room temperature photoluminescence	V. A. Sivakov	Phys. Rev. B.	82(2010)	American Physical Society	Ridge NY	2010	125446	http://prb.aps.org/abstract/PRB/v82/i12/e125446	no
5	Near-field investigations of nanoshell cylinder dimers	Katja Höflich,	THE JOURNAL OF CHEMICAL PHYSICS	131, 164704 2009	American Institute of Physics	Melville, N.Y.	2009		http://jcp.aip.org/resource/1/jcpsa6/v131/i16/p164704_s1	yes
6	In Situ Electron Microscopy Mechanical Testing of Silicon Nanowires Using Electrostatically Actuated Tensile Stages	Dongfeng Zhang	JOURNAL OF MICROELECTROMECHANICAL SYSTEMS	VOL. 19, NO. 3, 2010	IEEE American Society of Mechanical Engineers, ASME	New York	2010	663 - 674	http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5445050&tag=1	no
7	Gold catalyst initiated growth of GaN nanowires by MOCVD	J.-P. Ahl	Physica status solidi C	Volume 8, Issue 7-8, 2011	Akademie-Verlag	Berlin	2011	2315–2317	http://onlinelibrary.wiley.com/doi/10.1002/pssc.201000992/abstract	no
8	Ordered arrays of epitaxial silicon nanowires produced by nanosphere lithography and chemical vapor deposition	Damiana Lerose,	J. Cryst. Growth	312(20), (2010)	North-Holland	Amsterdam	2010	2887–2891	http://pubs.acs.org/doi/abs/10.1021/nl051856a	no
9	Optical properties of individual Silicon Nanowires for	Gerald Brönstrup,	ACS Nano	4(12), (2010)	ACS Publications	Washington	2010	7113-7122	http://pubs.acs.org/doi/abs/10.1021/nn101076t	no

	Photonic Devices									
10	Characterization of ZnO:Al/Au/ZnO:Al trilayers for high performance transparent conducting electrodes	Dimopoulos T	THIN SOLID FILMS	Volume: 519 Issue: 4 2010	Elsevier Sequoia	Lausanne	2010	p. 1470-1474,	http://resolver.scholarsportal.info/resolve/00406090/v519i0004/1470_coztfhptce	no
11	Photoluminescence of samples produced by electroless wet chemical etching: Between silicon nanowires and porous structures	Felix Voigt	Phys. Status Solidi A	Volume 208, (2011)	Akademie-Verlag	Berlin	2011	, 893-899/ DOI 10.1002/pssa.201026520	http://onlinelibrary.wiley.com/doi/10.1002/pssa.201026520/abstract	no
12	Chemical and Optical Characterisation of Atomic Layer Deposition Aluminium doped ZnO films for Photovoltaics by Glow Discharge Optical Emission Spectrometry	S. W. Schmitt	JAAS Journal of analytical atomic spectrometry	26, 2011	Royal Society of Chemistry	London	2011	822-827	http://pubs.rsc.org/en/content/articlelanding/2011/ja/c0ja00158a	no
13	Growth of doped silicon nanowires by pulsed laser deposition and their analysis by electron beam induced current imaging	B. Eisenhawer	Nanotechnology	22, 075706 2011	IOP Publishing	Bristol	2011	075706	http://iopscience.iop.org/0957-4484/22/30/305604/	yes
14	Growth of axial SiGe heterojunctions in nanowires using PLD	B. Eisenhawer	Nanotechnology	22, 305604 2011	IOP Publishing	Bristol	2011	305604	http://iopscience.iop.org/0957-4484/22/30/305604	yes
15	Increasing the efficiency of polymer	Björn Eisenhawer	Nanotechnology	22, 315401 2011	IOP Publishing	Bristol	2011	315401	http://iopscience.iop.org/0957-4484/22/31/315401	yes

	solar cells by silicon nanowires									
16	Statistical model on the optical properties of silicon nanowire mats	G. Brönstrup,	Physical Review B	84, 125432 2011	American Physical Society	Ridge NY	2011	125432	http://prb.aps.org/abstract/PRB/v84/i12/e125432	no
17	A precise optical determination of nanscale diameters of semiconductor nanowires	Gerald Brönstrup	Nanotechnology	22, 385201 2011	IOP Publishing	Bristol	2011		http://iopscience.iop.org/0957-4484/22/38/385201	yes
18	Photoluminescence and Raman Scattering in Arrays of Silicon Nanowires	V.Yu.Timoshenko	Journal of Nanoelectronics and Optoelectronics	Volume 6 Number 4,	American Scientific Publishers	Riverside California	2011	pp. 519-524(6)	http://www.ingentaconnect.com/content/asp/jno/2011/00000006/00000004/art00017	no
19	Self-catalyzed, vertically aligned GaN rod-structures by metal-organic vapor phase epitaxy	Christian Tessarek	Physica Status Solidi C	accepted	Akademie-Verlag	Berlin	2012	596–600	http://onlinelibrary.wiley.com/doi/10.1002/pssc.201100471/abstract	no
20	Influence of the Contacting Scheme in Simulations of Radial Silicon Nanorods Solar Cells	Felix Voigt	Material Science and Eng. B	(accepted)	Elsevier Seq.	Lausanne	2012		http://www.sciencedirect.com/science/article/pii/S0921510711005150	no
21	Effects of light localization in photoluminescence and Raman scattering in silicon nanostructures	K. A. Gonchar	Bulletin of the Russian Academy of Sciences: Physics	74(12)	Allerton Inc.	New York	2011	1782-1784	DOI: 10.3103/S1062873810120208	no
22	Glow Discharge Techniques in the Chemical Analysis of Photovoltaic Materials	S. W. Schmitt	Progress in Photovoltaics	accepted	Wiley	Weinheim	2012			

Books:

Vladimir Sivakov, Felix Voigt, Björn Hoffmann, Viktor Gerliz, Silke Christiansen, Wet- Chemically Etched Silicon Nanowire Architectures: Formation and Properties, Intech; "Nanowires - Fundamental Research", ISBN 978-953-307-327-9; ed. Abbass Hashim; Chapter 3; pp. 45-80 (2011).

Conferences & Workshops:

2009:

1. V. Sivakov, Th. Stelzner, A. Berger, M. Becker, G. Andrä, A. Gawlik, J. Plentz, G. Brönstrup, B. Eisenhawer, K. Ehrhold, D. Lerose, B. Hoffmann , Dongfeng Zhang, Ch. Niederberger, J. Michler, S.H. Christiansen „Silicon Nanowire Based Solar Cells on Glass: Concepts and experimental processing". QUANTSOL 2009, European Society for Quantum Solar Energy Conversion, Rauris, Salzburg, Austria; March 8-14.

2. V. Sivakov, R. Scholz, F. Syrowatka, F. Falk, U. Gösele and S. Christiansen, "Influence of Silicon Sidewall Structure's to the Silicon Nanowire Oxidation Processes". 1st GMM Workshop Mikro-Nano-Integration (VDE) Seeheim Lufthansa Training Center, Germany, March 12-13.

3. V. Sivakov , A. Berger, G. Andrae, A. Gawlik, F. Falk, S. H. Christiansen, "Silicon Nanowires: 1D Nanostructures and Perspectives in Photovoltaic". 1st GMM Workshop Mikro-Nano-Integration (VDE) Seeheim Lufthansa Training Center, Germany, March 12-13.

4. V. Sivakov, A. Gawlik, A. Berger, F. Falk, J. Plentz, U. Gösele, S. H. Christiansen, "Silicon Nanowire Based Solar Cell on Glass: Optic and Application in Photovoltaic". MRS Spring Meeting, San Francisco, USA, 13-17th April.

5. G. Brönstrup, V. Sivakov, Th. Stelzner, X. Mäder, Ch. Niederberger, J. Michler, S.H. Christiansen, „Silicon nanowire based solar cell on glass: growth, materials integration and characterization". MRS Spring Meeting, San Francisco, USA, 13-17th April.

6. S. H. Christiansen, S. Hoffmann, V. Sivakov, C. Ronning, J. Michler, U. Gösele, „Axial pn-junctions in Si nanowires by ion implantation".
MRS Spring Meeting, San Francisco, USA, 13-17th April.

7. Sivakov V.; M. Becker, K. Höflich, A. Berger, T. Stelzner, K.E. Elers, V. Pore, M. Ritala, S. Christiansen, "Ag//Pt core-shell nanostructure on Si nanowires: ALD processing and application in surface enhanced (resonant) Raman spectroscopy". MRS Spring Meeting, San Francisco, USA, 13-17th April.

8. Sivakov V.; M. Becker, K. Höflich, A. Berger, T. Stelzner, K.E. Elers, V. Pore, M. Ritala, S. Christiansen, "Ag//Pt core-shell nanostructure on Si nanowires: ALD processing and application in surface enhanced (resonant) Raman spectroscopy". 4th International Conference on Surface Plasmon Photonics (SPP4), Amsterdam, The Netherlands, 21-26 June.

9. S.H. Christiansen, V. Sivakov, G. Brönstrup, Th. Stelzner, C. Ronning, S. Hoffmann, J. Michler, „Doping strategies for silicon nanowires: ion implantation, diffusion and co-doping during chemical vapour deposition (CVD)". CECAM 2009 "Dopants and Impurities in Semiconducting Nanowires", Lausanne, Switzerland, July 6-8th.

10. Vladimir A. Sivakov, Annett Gawlik, Gudrun Andrä, Fritz Falk, Andreas Berger, Silke H. Christiansen, "3rd Generation Solar Cell Prototype Based on Chemically Formed Silicon Nanowires: Processing, Optical and Photovoltaic Properties". 24th EU PVSEC, Hamburg, Germany, September 21-25th.

11. V. Sivakov, A. Gawlik, A. Berger, F. Falk, J. Plentz, U. Gösele, S. H. Christiansen, "Silicon Nanowire Based Solar Cells on Glass: Concepts and experimental processing". NANOTECH EUROPE 2009, Berlin, Germany, September 28-30th.

12. V. Sivakov, M. Becker, K. Ehrhold, A. Berger, T. Stelzner, K. E. Elers, V. Pore, M. Ritala, S. Christiansen, "Ag//Pt Core Shell Nanostructure on Si Nanowires: ALD Processing and Application in Surface Enhanced (Resonant) Raman Spectroscopy". NANOTECH EUROPE 2009, Berlin, Germany, September 28-30th.

13. Vladimir A. Sivakov, Annett Gawlik, Andreas Berger, Silke H. Christiansen, "3rd Generation Solar Cell Prototype Based on Chemically Formed Silicon Nanowires: Processing, Optical and Photovoltaic Properties". GADEST 2009, Berlin, Germany, September 26th-October 2nd.

14. Vladimir A. Sivakov, F. Voigt, Silke H. Christiansen "Solar Cell Based on Etched Silicon Nanowires: Formation and Optoelectronic Properties". 2. Photovoltaik-Symposium "Solare Energieversorgung –quo vadis", November 5-6, 2009 Bitterfeld-Wolfen, Germany

2010:

1. Th. Stelzner, V. Sivakov, A. Berger, B. Hoffmann, S. De Wolf, Ch. Ballif, D. Zhang, J. Michler, S. H. Christiansen, Structural, Optical, and Electrical Properties of Silicon Nanowires for Solar Cells", IEEE International NanoElectronics Conference, Hong Kong, China, 3-8.01.2010

2. Vladimir A. Sivakov, Björn Hoffmann, Felix Voigt, Andreas Berger, Gottfried Bauer, Silke H. Christiansen, Visible room temperature photoluminescence in silicon nanowires, 7th International Conference PSST-2010, Valencia, Spain, 14-19.03.2010

3. F. Voigt, V. Gerliz, V. Sivakov, G. H. Bauer, and S. Christiansen, Photoluminescence of Wet Chemically Etched Silicon Nanowires, QUANTSOL 2010 Winter workshop, Brigels (Breil), Switzerland, 07-13.03.2010

4. Gerald Brönstrup, Norbert Jahr, Christian Leiterer, Andrea Csáki, Silke Christiansen, Optical properties of crystalline silicon nanowires, QUANTSOL 2010 Winter workshop, Brigels (Breil), Switzerland, 07-13.03.2010

5. B. Hoffmann, G. Brönstrup, U. Hübner, S.H. Christiansen, Epitaxial silicon nanowire growth catalyzed by gold dot arrays from electron beam lithography patterning using silane precursors, DPG Frühjahrstagung 2010, Regensburg, Germany, 21-26.03.2010

6. Björn Hoffmann, Christoph Niederberger, Gerald Brönstrup, Uwe Hübner, Silke Christiansen, Fabrication of single crystalline gold nanodots on silicon substrates: a combined EBL & VLS-CVD-process, DPG Frühjahrstagung 2010, Regensburg, Germany, 21-26.03.2010

7. G. Brönstrup, S. Christiansen, Optical properties of carpets of randomly grown silicon nanowires on glass, DPG Frühjahrstagung 2010, Regensburg, Germany, 21-26.03.2010

8. S. Milz, V. Sivakov, G. Brönstrup, M. Gnauck, R. Niepelt, S. Christiansen, C. Ronning, DPG Frühjahrstagung 2010, Regensburg, Germany, 21-26.03.2010

9. Björn Hoffmann, Gerald Brönstrup, Uwe Hübner, Damiana Lerose, Silke Christiansen; Epitaxial silicon nanowire growth catalyzed by gold dot arrays from electron beam lithography patterning using silane precursors, MRS Spring Meeting 2010, San Francisco, USA, 5-9.04.2010

10. F. Voigt, G. H. Bauer, V. Sivakov, A. Berger and S. Christiansen, PL Properties of Si-NWs produced by WCE using varying etching conditions, MRS Spring Meeting 2010, San Francisco, USA, 5-9.04.2010

11. D. Lerose, M. Jenke, M. Bechelany, Ch. Niederberger, L. Philippe, I. Utke, J. Michler, S. Christiansen, Two Synthesis Methods of Au Dot Arrays for Catalyzing Epitaxial Ordered Si Nanowire, MRS Spring Meeting 2010, San Francisco, USA, 5-9.04.2010

12. S. Christiansen, Semiconductor Nanowires in Novel Device Concepts: the need for Structural and Mechanical Integrity and Ways to Reliably Characterize these Properties, 37th International Conference on Metallurgical Coatings & Thin Films, San Diego, USA, 26-30.04.2010

13. Felix Voigt, Gottfried H. Bauer, Vladimir Sivakov, Andreas Berger, Silke Christiansen, Photoluminescence Properties of Silicon Nanowires Produced by Wet Chemical Etching Using Varying Etching Conditions, EMRS Spring Meeting 2010, Strasbourg, France, 7-11.06.2010

14. Vladimir A. Sivakov, Björn Hoffmann, Gerald Brönstrup, Felix Voigt, Matthias Pietsch, Silke Christiansen, New Thin Film Solar Cell Concepts Based on Silicon Nanowires on Glass as well as in Polymer Matrix, 8th International Conferenceon Coating on Glass and Plastics, Braunschweig, Germany, 13-17.06.2010

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COMPANIES:

PV is one of Picosun Oy's central target business segments of the future. In 2011, Picosun Oy has participated in several conferences & expos and delivered speeches and posters in which also ALD's (Atomic Layer Deposition) PV applications, including the potential of ALD in novel solar cell technologies such as the one developed in the project ROD-SOL, have been covered. These conferences & expos include the NSTI Nanotech in Boston, USA, June 2011 (http://www.techconnectworld.com/Nanotech2011), the 26th EU PVSEC conference & expo in Hamburg, September 2011 (http://www.photovoltaic-conference.com/previous-eupvsec/26th-eu-pvsec.html), where Picosun also had a stand, and the 220th ECS meeting in Boston, USA, October 2011 (http://www.electrochem.org/meetings/biannual/220/220.htm).

Picosun Oy has also published several PV-themed press releases, the most important considering the project being from December 2011: http://www.picosun.com/news/2011/311211.php. This press release also got the attention of other PV journals and Picosun Oy was asked to deliver more detailed articles about the project results to these journals. Currently (7 Feb, 2012), a full-scale scientific article is being constructed in cooperation with Max Planck Institute (Mr. Björn Hoffmann and Dr. Silke Christiansen) to the InterPV journal (http://www.interpv.net/) and SVConnections (Society of Vacuum Coaters) e-newsletter (http://www.svc.org/Publications/SVConnections.cfm) has also linked Picosun's press release in its February 2012 issue. This way, Picosun Oy has been active in "spreading the word", advertising the project and bringing its results to the attention of global audience.

Section B (confidential)

During the project, Picosun Oy has developed and optimized ALD processes (antimony oxide Sb_2O_3 and zinc-doped aluminium oxide $Zn:Al_2O_3$) for potential industrial applications. Also, plans for process upscaling and development and construction work of large ALD tools for high volume industrial manufacturing has been carried out during the project.

TEMPLATE B2: OVERVIEW TABLE WITH EXPLOITABLE FOREGROUND					
Exploitable Foreground (description)	**Exploitable product(s) or measure(s)**	**Sector(s) of application**	**Timetable, commercial use**	**Patents or other IPR exploitation (licences)**	**Owner & Other Beneficiary(s) involved**
MOCVD PROCESS KNOW HOW FOR CATALYZED AND CATALYST FREE GAN NR GROWTH ON GAN TEMPLATES	MOCVD PROCESS KNOW HOW	SEMICONDUCTOR INDUSTRIE	2012		AIXTRON SE, MPRG-FAU
PRELIMINARY PROCESS RESULTS FOR CATALYST FREE GAN NR GROWTH ON SI SUBSTRATES	MOCVD PROCESS KNOW HOW	SEMICONDUCTOR INDUSTRIE	2012		AIXTRON SE, MPRG-FAU
MOCVD EQUIPMENT ASSESSMENT REGARDING REQUIREMENTS FOR GAN NR GROWTH	OPTIMIZED MOCVD EQUIPMENT FOR DEPOSITION OF GAN BASED NR	SEMICONDUCTOR INDUSTRIE	2013-14		AIXTRON SE

EXPLOITATION / DISSEMINATION - AIXTRON SE

The future industrial use of III-N based NRs for solar cell applications strongly depends on the availability of a cost competitive production technology. MOCVD cost of ownership is driven by higher system throughput, e.g. shorter process cycle times and faster reactor loading times, higher reactor capacities, and ever improving production reproducibility. As the market availability is driven by cost, and MOCVD is one of the driving cost factors for opto-electronic components and high efficiency III-V semiconductor based solar cells, the requirements on MOCVD technology is steadily increasing.

In the frame of RodSol AIXTRON further developed MOCVD technology, hardware and processes, meeting future requirements related to cost driving factors like, yield, production stability and overall throughput. Decreasing cost of ownership for mass production of III-N based NRs for solar cell applications shall gain market growth again.

- **MOCVD PROCESS KNOW HOW FOR CATALYZED AND CATALYST FREE GAN NR GROWTH ON GAN TEMPLATES**
- **PRELIMINARY PROCESS RESULTS FOR CATALYST FREE GAN NR GROWTH ON SI SUBSTRATES**

AIXTRON will profit twice from the process know-how gained within RodSol. First of all, the deep understanding of specific MOCVD processes is the basis for all MOCVD equipment engineering. Therefore the process-know how, developed in the frame of RodSol, will help AIXTRON to optimize the industrial MOCVD equipment for the deposition of GaN-based NRs on GaN-sapphire templates and on large area Si wafers. AIXTRON will use the RodSol results as basis for the development of a new series of MOCVD production tools for the cost effective production of GaN based NRs on diverse substrates, fulfilling all industry standards in terms of yield, production stability and overall throughput. Certainly this new materials will not be limited to applications in the field of solar power generation but offers also significant potential to be used in high brightness LEDs.
Secondly, AIXTRON needs certain process know-how for process demonstrations for customers. The process know-how will be used to demonstrate the potential of the optimized MOCVD equipment for advertising purpose.

- **MOCVD EQUIPMENT ASSESSMENT REGARDING REQUIREMENTS FOR GAN NR GROWTH**

Within the RodSol project, AIXTRON has assessed the MOCVD R&D equipment regarding special requirements for the deposition of GaN-based NRs. In many details the equipment has been optimized already in the course of the project. The extreme low V-III ratios for example, needed to switch the GaN growth process from film growth to wire growth, required an adaptation of the gas mixing system. RodSol helped to optimize two different types of R&D MOCVD tools for the deposition of GaN based NRs. The first tool was the horizontal flow tube reactor AIX200 placed at MPRG-Fau, the second one the vertical flow Close Coupled Showerhead® (CCS) reactor placed in the AIXTRON application laboratory. After the successful technology development in the frame of RodSol, AIXTRON will use the RodSol results as basis for the development of a new series of MOCVD production tools. The early stage of technology development for the application of GaN based NRs in solar cells makes a quantitative forecast of the future business difficult. But we are confident, that at least GaN-NR based LEDs have a significant market potential. RodSol helped to have optimized MOCVD production equipment available as soon as the final technological challenges for the application of GaN based NR in solar cells and LEDs have been solved.
Thus, RodSol improve the competitiveness of AIXTRON reactors for the emerging market of NR based solar cells and optical devices like LEDs and lasers. RodSol will strengthen AIXTRON's position as European and world leading-manufacturer of MOCVD equipment and will support the sustainable creation of new employment at AIXTRON as well as on the sub-supplier and end user site.

VI Report on societal implications

Replies to the following questions will assist the European Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A	**General Information** *(completed automatically when **Grant Agreement number** is entered.*
Grant Agreement Number:	227497
Title of Project:	ROD SOL
Name and Title of Coordinator:	Dr. Silke Christiansen

B Ethics		
1. Did you have ethicists or others with specific experience of ethical issues involved in the project?	O X	**Yes** **No**
2. Please indicate whether your project involved any of the following issues (tick box) :	***YES***	
INFORMED CONSENT		
• Did the project involve children?		
• Did the project involve patients or persons not able to give consent?		
• Did the project involve adult healthy volunteers?		
• Did the project involve Human Genetic Material?		
• Did the project involve Human biological samples?		
• Did the project involve Human data collection?		
RESEARCH ON HUMAN EMBRYO/FOETUS		
• Did the project involve Human Embryos?		
• Did the project involve Human Foetal Tissue / Cells?		
• Did the project involve Human Embryonic Stem Cells?		
PRIVACY		
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)		
• Did the project involve tracking the location or observation of people?		
RESEARCH ON ANIMALS		
• Did the project involve research on animals?		
• Were those animals transgenic small laboratory animals?		
• Were those animals transgenic farm animals?		
• Were those animals cloning farm animals?		
• Were those animals non-human primates?		
RESEARCH INVOLVING DEVELOPING COUNTRIES		
• Use of local resources (genetic, animal, plant etc)		
• Benefit to local community (capacity building ie access to healthcare, education etc)		
DUAL USE		
• Research having potential military / terrorist application		

C	Workforce Statistics	
3 Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).		
Type of Position	**Number of Women**	**Number of Men**
Scientific Coordinator	1	0
Work package leader	4	6
Experienced researcher (i.e. PhD holders)	4	9
PhD Students		3
Other	3	9

4 How many additional researchers (in companies and universities) were recruited specifically for this project?	
Of which, indicate the number of men:	4
Of which, indicate the number of women:	3

D Gender Aspects

5	**Did you carry out specific Gender Equality Actions under the project** ?	X O	Yes No

6 Which of the following actions did you carry out and how effective were they?

		Not at all effective				Very effective
X	Design and implement an equal opportunity policy	O	O	O	X	O
X	Set targets to achieve a gender balance in the workforce	O	O	O	X	O
❑	Organise conferences and workshops on gender	O	O	O	O	O
❑	Actions to improve work-life balance	O	O	O	O	O
X	Other: set up internal “Equal Gender Policies”					

7 Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

X Yes- please specify

The female share in students, researchers and engineers in the area of micro systems technology, especially robotics or microelectronics and other areas of electronics such as large area or opto-electronics is still behind the proportion of women in other professions. The EU legislation and the country specific implementations have contributed to sharpen consciousness and foster the creation of structures for more gender-fairness. At present, women constitute only around 15% of industrial researchers in Europe. Since the consortium is aware of gender issues in research and engineering, it established the role of a ***Gender Manager*** who has ensured that all gender issues related to this project were taken seriously into account and dedicated actions to resolve these issues were performed. This was done by setting up a gender action plan, which was continuously updated during the runtime. Due to the lower participation of female scientists and engineers within ROD_SOL, partners of the consortium essentially concentrated the Gender action plan on the projects’ internal level with following aims:

- The sensitisation of involved project partners for equal opportunities in the context of research and developments in ROD_SOL
- The support of female members of the consortium by internal and external networking.
- The enhancement of the specific contribution made by women in the processes of R&D, as well as in management (e.g. conflict resolution).

Therefore, the ***Gender Action Plan*** of ROD_SOL was linked to the corresponding activities of the partners:

- The partners actively requested their female employees and students to participate in the project work as well as in staff a mobility program, which provided an excellent opportunity to gain access to the important but informal professional networks.
- All partners have utilised their networks, for instance IPHT and MPRG using the competence centres “Women in the Information-Society and -Technology”, the female engineering network of VDI (association of German engineers) and other equal gender institutions to approach this target group.
- Furthermore, most ROD_SOL partners have already set up internal “Equal Gender Policies”

The field of silicon thin film photovoltaic is not influenced by social prejudices or by real situations leading to “typical male jobs”. This is illustrated by the presence within ROD_SOL of a female consortium manager. Moreover, it is important to emphasize that the technologies to

	be developed and in use do not require body strength which would place men in a certain advantage. Therefore, ROD_SOL does not pose physical disadvantages either for women or for other collectives that have been denied access to jobs in traditional industrial sectors. This new PV material and instrumentation of ROD_SOL is well suited for any individual, regardless of their gender to be worked on. Technical and intellectual skills are the main requirements of the jobs created by the introduction of a novel thin film silicon technology based on NRs, instrumentation and process developments.

E Synergies with Science Education

8 Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

X Yes- please specify

Student colloquiums: In order to allow an optimum dissemination of the results from an educational perspective, student colloquiums were organised approximately once a year. In the talks and tutorials, special care was paid to the comprehensibility for students.

○ No

9 Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

○ Yes- please specify

○ No

F Interdisciplinarity

10 Which disciplines (see list below) are involved in your project?

X Main discipline[8]: 1.2

X Associated discipline[8]: 2.2 | X Associated discipline[8]: 2.3

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*	○ X	Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

○ No

○ Yes- in determining what research should be performed

○ Yes - in implementing the research

○ Yes, in communicating /disseminating / using the results of the project

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No

12 Did you engage with government / public bodies or policy makers (including international organisations)

○ No

○ Yes- in framing the research agenda

○ Yes - in implementing the research agenda

○ Yes, in communicating /disseminating / using the results of the project

[8] Insert number from list below (Frascati Manual)

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

- ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- ○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- ○ No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport	

13c If Yes, at which level?

- ○ Local / regional levels
- ○ National level
- ○ European level
- ○ International level

H	Use and dissemination	
14	**How many Articles were published/accepted for publication in peer-reviewed journals?**	**22**
	To how many of these is open access[9] provided?	**6**
	How many of these are published in open access journals?	**3**
	How many of these are published in open repositories?	**3**
	To how many of these is open access not provided?	**16**
	Please check all applicable reasons for not providing open access:	
	Xpublisher's licensing agreement would not permit publishing in a repository X no suitable repository available X no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other: ……………	
15	**How many new patent applications ('priority filings') have been made?** *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**0**

16	**Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).**	Trademark	**0**
		Registered design	**0**
		Other	**0**

17	**How many spin-off companies were created / are planned as a direct result of the project?**	**-**
	Indicate the approximate number of additional jobs in these companies:	

18 Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑	Increase in employment, or	❑	In small & medium-sized enterprises
❑	Safeguard employment, or	❑	In large companies
❑	Decrease in employment,	X	None of the above / not relevant to the project
X	Difficult to estimate / not possible to quantify	❑	

19	**For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:**	*Indicate figure:*
	Difficult to estimate / not possible to quantify	X

[9] Open Access is defined as free of charge access for anyone via the internet.

I Media and Communication to the general public

20 As part of the project, were any of the beneficiaries professionals in communication or media relations?

X Yes ○ No

21 As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes X No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

X	Press Release	X	Coverage in specialist press
X	Media briefing	X	Coverage in general (non-specialist) press
❑	TV coverage / report	X	Coverage in national press
❑	Radio coverage / report	❑	Coverage in international press
X	Brochures /posters / flyers	X	Website for the general public / internet
❑	DVD /Film /Multimedia	X	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

❑	Language of the coordinator	X	English
❑	Other language(s)		

***Question F-10*: ** Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES
1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]
1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)
1.3 Chemical sciences (chemistry, other allied subjects)
1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)
1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY
2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)
2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]
2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised

technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group] .