Scientific and technological results

To reach the targets presented in the previous section, PhotoNVoltaics is organised into five work packages, from which the first three concern technological developments: the design of the nanopatterns by modelling (WP1), their realisation (WP2) and their integration into solar cells (WP3). Cost calculations, and the dissemination of results, are dealt with in WP4, while communication with the EC and within the consortium is taken care of in WP5. An essential task is to ensure the good daily communication between WP1, 2 and 3, which are strongly interdependent. A constant interaction is needed both between work packages and between partners, leading to a large number of samples to be exchanged between France, Belgium and Sweden.

The general work strategy to reach the end goals is to proceed with three iterations of solar cell fabrication. Each iteration integrates the developments achieved so far in nanopatterns, both in identifying which patterns are best (both for periodic and non-periodic structures) and how to best fabricate and integrate them so that not only the optical properties, but also the electrical properties of the cell are good. Finding the most harmless processes is the cornerstone of the project. Then, the findings at each of the cell iterations let us focus the next development steps on the most promising configurations. The various questions to be answered over the three years of the project for a successful solar cell integration are schematically summarised in the figure below.

The main findings of the four work packages are briefly summarised in the following sections. At the end of each section, peer-reviewed publications are listed for further reading.

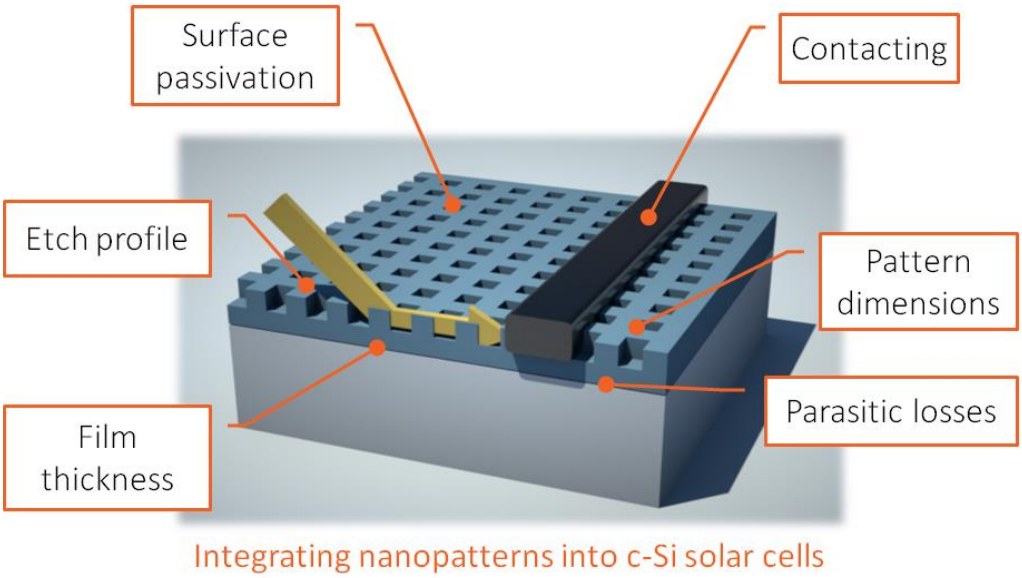


Figure 1: An essential target of PhotoNVoltaics is to determine the characteristics of a nanopatterned thin-film c-Si solar cell.

A. Modelling nanopatterns

Computer modelling is the most convenient approach, in terms of time and effort, for identifying the most beneficial nanopattern morphology (i.e. its pitch, filling fraction, and profile shape) to reach the highest short-circuit current (Jsc) possible for a specific solar cell architecture. An essential result of PhotoNVoltaics is the setting up of a wide range of numerical tools to assess the impact of nanopatterned surfaces in solar cells. Optical modelling was performed by two partners, CNRS-INL and UNamur, with two different and complementary techniques; FDTD (Finite Difference Time Domain) and Rigorous Coupled Wave Analysis (RCWA). On top of this, electrical simulations could be coupled to these models via Silvaco (a task of CNRS-INL). Finally, for a rigorous and realistic assessment, these models were fed with actual optical and electrical constants measured for the materials (silicon films, antireflective coatings, passivation coatings, metals, etc.) available in the consortium.

Only functional and complete cell structures were modelled, and the short-circuit current-density (Jsc) – our figure of merit – was calculated by extracting only the absorption inside the c-Si thin film composing the cell. Optical simulations typically outcome the photon absorptance of the given structure. Absorptance is also the value that can be measured most straightforwardly in experiments. However, the absorptance of the complete stack (with antireflective coating, rear-reflector, ...) is not directly giving an output of the Jsc, since only a few of the layers will actually generate electrons that can be collected by the contacts. This is illustrated in Figure 2, that displays the absorptance (A, black) and the Jsc (EQE, purple) extracted from a flat and a nanopatterned 1-µm-thin solar cell, showing that a high light absorption does not necessarily correspond to a high Jsc, since part of that absorbed light is lost in front-side and rear-side layers.

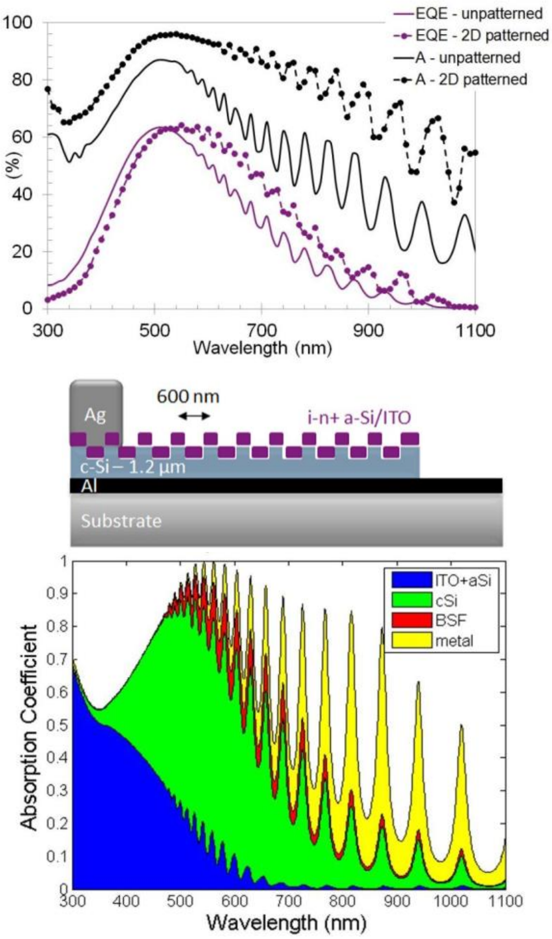


Figure 2: (top) Absorptance and EQE of a 1-µm-thin solar cell (middle) with a flat or nanopatterned front surface. (bottom) Modelled localized absorption spectra of the unpatterned cell in terms of absorption efficiency, isolating the contributions of each layer [Depauw2014a].

Extraction of the Jsc hence requires isolating the number of photons that are absorbed in electrically active layers, i.e. in our case the c-Si base. This is what our models calculated, both via FDTD and RCWA. Our studies were based on the calculation of the light-absorption efficiency of the cell:

$$\eta = \frac{\Phi_a}{\Phi_i} = \frac{\int \frac{\lambda}{hc} S(\lambda) A(\lambda) d\lambda}{\int \frac{\lambda}{hc} S(\lambda) d\lambda}$$

where Φa and Φi are respectively the absorbed photon flux and the incident photon flux, $A(\lambda)$ is the absorption coefficient in the active layer (given by simulations by FDTD or RCWA) and $S(\lambda)$ is the normalized solar spectrum AM1.5G. Under the hypothesis of a perfect internal quantum efficiency, the short circuit current density of the cell is $Jsc = e\Phi a$ where e is the charge of the electron. It can be noticed that a complete sunlight absorption by the silicon would lead to a Jsc of 43.5 mA/cm^2.

Optical modelling first strived to determine the characteristic dimensions of an optimal pattern, in function of the thickness of the silicon foil and the type of solar cell to be processed. The silicon foil thickness that we explored covered the typical thin-film crystalline silicon range, from 1 to 40 µm. The large number of potential cases to be modelled was limited by experimental "boundary conditions", that were explored in WP2 and WP3 to determine what is experimentally achievable. In the case when a limited number of parameters had to be explored, a systematic parameter scan was performed. An example of such a scan and the resulting optimisation maps are shown in Figure 4 for a a-Si:H/c-Si heterojunction solar cell with two-side contacts. This scanning map allows determining large areas of optimum values, in order to take into account the experimental profile tolerances. The maps, shown for the case of a 2D pattern with a "super-gaussian" hole profile, show that patterns with a high filling fraction - that is with a diameter as wide as possible with respect to their pitch - should be targeted. Moreover, a comparison with a 2D pattern of nano-pyramidal holes showed that the latter perform better. Also, not surprisingly, the interesting photonic effects are mostly efficient for micron-scale films rather than in thicker ones.

In the case when a larger number of parameters (for instance the period and the filling fraction of the pattern and the thickness of 4 different layers composing the cell) had to be optimised all together, then a genetic algorithm was used. This custom-made algorithm, developed at UNamur, provided a "smart" scan that converged progressively to the complete optimum set of values without enduring an exponential explosion of computing time. The strategy consists in selecting from generation to generation the fittest individuals of a population (each individual is representative of a given set of parameters). New individuals are generated by crossing these selected individuals and by introducing random mutations in the coding of parameters. By this evolutionary strategy, the population generally converges to globally optimal solutions.

A second task of optical modelling was the thorough study of the impact of perturbations in a perfectly periodic nanopattern, a recurrent question in photonics literature in the past few years. Two different modelling approaches were followed, that enable covering different degrees of disorder, from a pseudo-disordered pattern to a quasi-random (or pseudo-periodic) pattern (Figure 3).

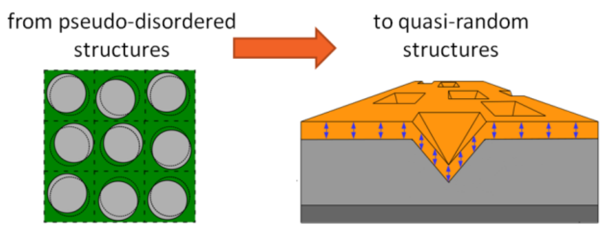
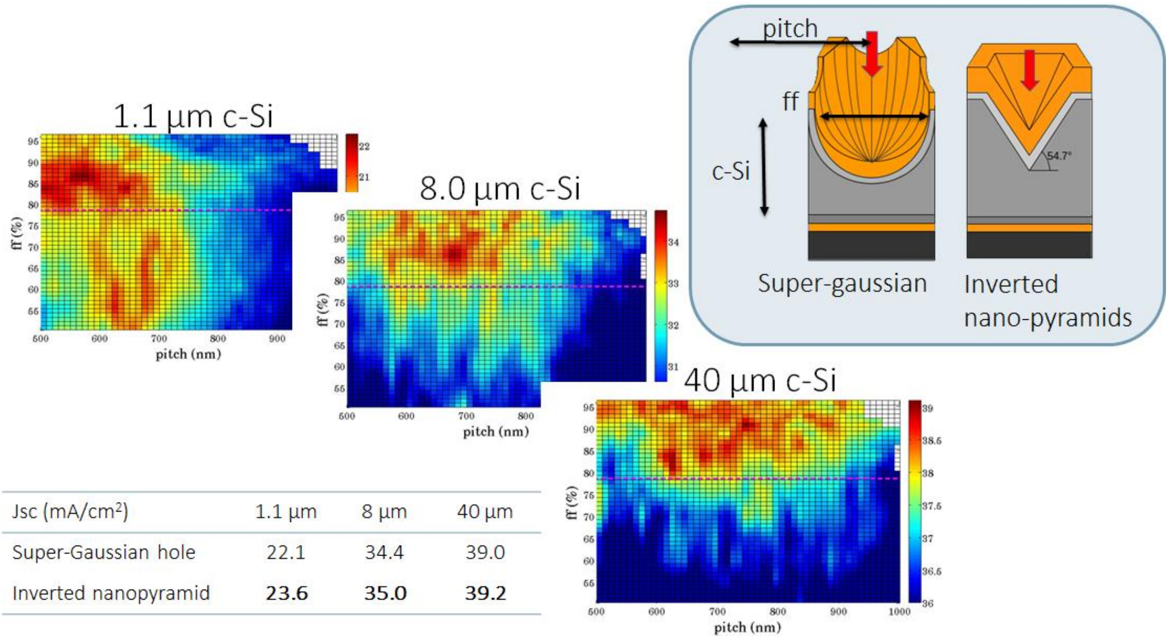


Figure 3: Our two modelling approaches for a graded disruption of periodicity.



Jsc (mA/cm^2)	1.1 µm	8 µm	40 µm
Super-Gaussian hole	22.1	34.4	39.0
Inverted nanopyramid	**23.6**	**35.0**	**39.2**

Figure 4: Highest values of Jsc of two-side contacted heterojunction cells obtained by a scan of the nanopattern's filling fraction and pitch, modelled for three different film thicknesses and for two pattern profiles. The Jsc maps are shown for a "super-gaussian" hole profile [Depauw2014b].

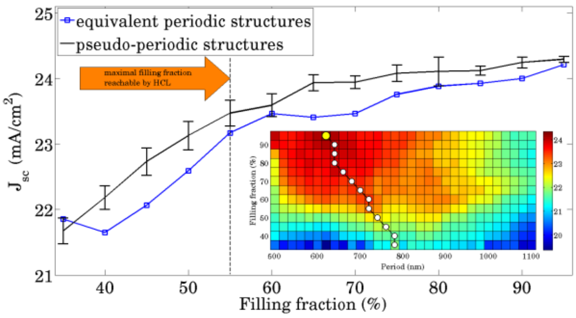


Figure 5: Modelled Jsc for an optimised periodic pattern – optimised with a given filling fraction (inset) – and the higher Jsc of its pseudo-periodic counterpart [Muller2015]. The arrow indicates the maximum fill fraction that could be achieved experimentally in the frame of the project.

The two different approaches confirm that the disruption of periodicity is beneficial for a wide range of film thicknesses, but only for a limited degree of disorder. We also found that, if pseudo-periodic or pseudo-disordered structures can both bring an increase in Jsc compared to periodic structures, it should be stressed that for front-side nanopatterns, the most important parameter is a high filling fraction (Figure 5). This indeed optimises the in-coupling of all incoming photons inside the silicon film, thanks to the progressive gradient in refractive index that is introduced, as a transition from air to silicon.

Overall, our models show that it is possible to reach competitive Jsc values from thin films that are a few tens of micrometres thick. For instance, with 40 µm of c-Si, a solar cell (without encapsulation) with a Jsc above 40 mA/cm^2 may be achievable. A strong limitation of this Jsc is originating from the parasitic absorption by non-optically active layers of the solar cell, such as the rear metal contact. If their absorption can be minimised by carefully choosing these materials and playing with constructive and destructive interferences inside the stack, it seems that they may stay a strong barrier for breaking beyond the theoretical benchmark limits of light absorption in solar cells. Double-side, rather than front-side texturing only, brings a significant improvement in light trapping. However, the relative gain decreases as the film thickness increase and, besides, one should bear in mind that the cost of a double-side texture may prohibit their implementation in an industrial process, unless creative texturing solutions are found.

In view of optimising both the light-trapping efficiency of a pattern and its antireflective effect, we find that inverted nanopyramids are the best pattern profile, compared to "Gaussian" holes, cylinders or domes. They are fortunately also the best choice for the electrical performance of the cell. This experimental finding was also studied by modelling, to understand the importance of micro-roughness, or of different types of defects of the surface passivation coating the pattern. Opto-electrical modelling was also used to determine whether the solar cell emitter should rather be positioned at the front nanopatterned side, or at the flat shadow side, on the rear (Figure 6). Eventually, this helps understanding why certain nanopatterns damage the cell's functioning, and deciding how to proceed with the different fabrication steps.

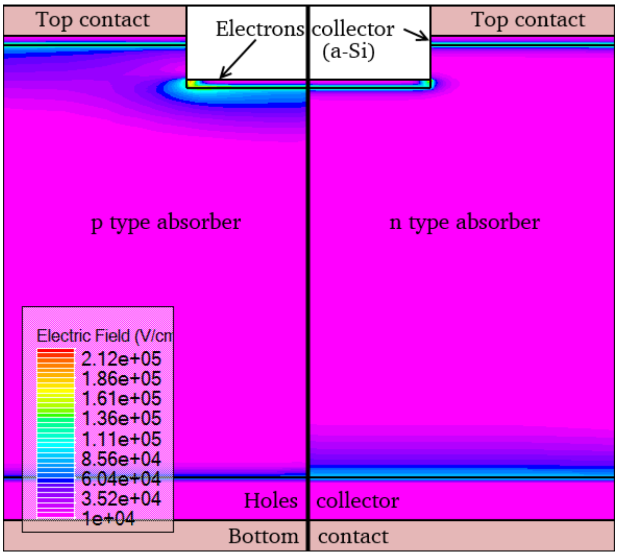


Figure 6: Map of the electrical field at maximum efficiency for a front-side (left) and rear-side (right) emitter cell nanopatterned with 2D cylinders [Mandorlo2013], without a-Si:H on the pattern side walls.

Further reading

- [Muller2015J Muller et al., A fair comparison between ultrathin crystalline-silicon solar cells with either periodic or correlated disorder inverted pyramid textures, 10.1364/OE.23.00A657
- R. Peretti et al., Absorption control in pseudodisordered photonic-crystal thin films, 10.1103/PhysRevA.88.053835
- [Mandorlo2013] F. Mandorlo et al., Electro-Optical Optimization of c-Si Thin Solar Cells Patterned by Photonic Crystals, 10.4229/28thEUPVSEC2013-3DV.1.9
- A. Mayer et al., Optimized absorption of solar radiations in nano-structured thin films of crystalline silicon via a genetic algorithm, 10.1117/12.2185672
- L. Lalouat et al., Pseudo-disordered structures for light trapping improvement in mono-crystalline Si thin-films, submitted

B. Fabricating nanopatterns

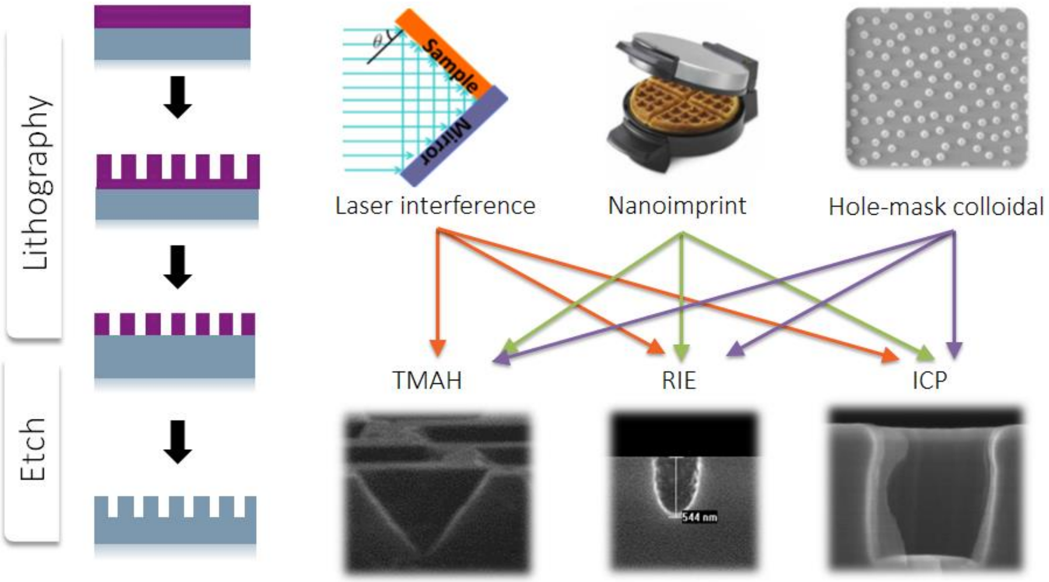


Figure 7: Lithography and etching techniques available in the consortium.

The project approach for the fabrication of nanopatterns was to consider techniques that not only lead to excellent light absorption, but that at the same time may be potentially applied to the PV industry, and that may deliver samples that could confront our optical models to reality. For this, the consortium could rely on laser-interference lithography (LIL), nanoimprint lithography (NIL) and hole-mask colloidal lithography (HCL) (Figure 7). The first is versatile and enables tuning the pattern pitch and diameter rather simply. Nanoimprint on the other hand has the advantage of being mature and is a good candidate for industrial application. Finally, hole-mask colloidal lithography can provide tunable pseudo-periodic structures, with a good range of hole diameters and average pitches. These three lithographies are to be combined with an etching step, to transfer the pattern into the silicon surface. For this, different dry-etching (mainly reactive ion etching) and wet etching (mainly with tetramethylammonium hydroxide) methods were compared. LIL was available at CNRS-INL, NIL at the company OBDUCAT, and HCL was developed by CHALMERS.

NIL and HCL were proven to result in uniform and reproducible patterns, on surfaces as wide as a full wafer area (Figure 8). They were also tested on wafers with different levels of roughness. If NIL was affected by roughness, HCL demonstrated to be perfectly applicable to extreme surface roughnesses.

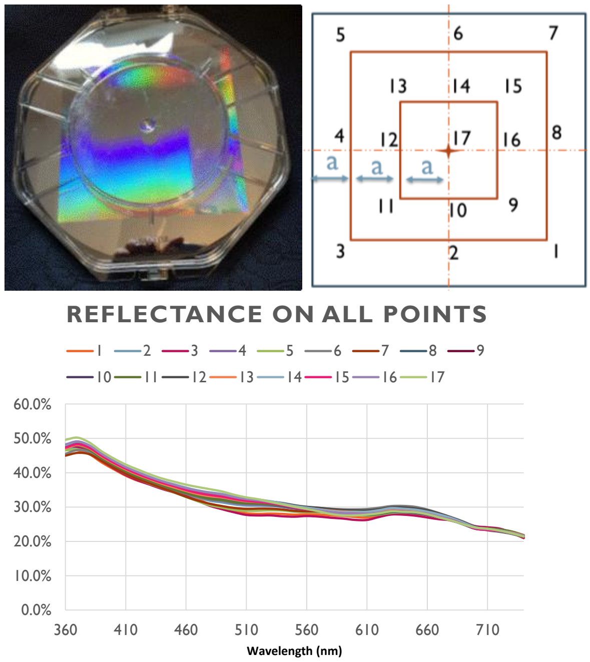


Figure 8: 200-mm wafer after NIL over an area of 130 x 130 mm and its uniform reflectance measured on short wavelengths and over the full patterned area.

The first goal with our nanopatterning techniques was to realise nanopatterns that improve the light trapping in c-Si films. An example of wet-NILed nanopatterned film, compared to the benchmarking standard texture of micron-scale random pyramids is shown in Figure 9. The sample is a bare foil with a textured front side that was bonded to glass with a highly transparent silicone. The absorptance measurement – in which we can assume the absence of parasitic absorption - shows clearly that the nanopattern leads to a better collection of longer wavelength photons than the random micron-scale pyramids. On the shorter wavelengths, the presence of glass and silicone has an averaging effect for the three patterns.

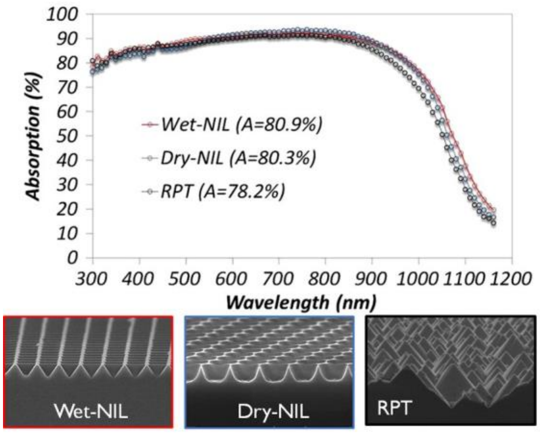


Figure 9: Absorptance curve of a bare 40-µm-thin c-Si foil textured with random micron-scale pyramids and nanoimprinted structures with parabolic-shaped holes (dry-NIL) and inverted nanopyramids (wet-NIL).

Next to the light trapping effect, another optical asset of nanopatterns is their robustness with respect to the light's angle of incidence (Figure 10).

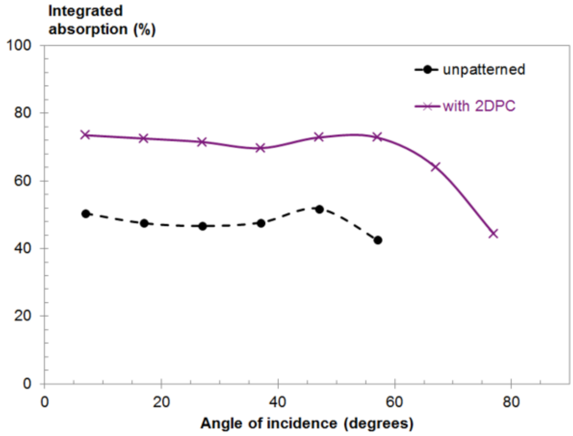


Figure 10: Integrated absorption of the unpatterned (black circles) and nanopatterned (purple crosses) solar cells under various angles of incidence of light, showing the nanopattern stays efficient until a high angle [Depauw2014a].

The second goal in nanopatterning was to explore a maximum of experimental possibilities and to identify our boundary conditions for creating nanopatterns. These findings were then used to evaluate and guide our modelling work. Figure 11 illustrates such a "boundary condition" for wet-etching of disordered structures, and Figure 12 shows how, as expected from theory, the introduction of disorder in a periodic pattern leads to the broadening and flattening of resonance mode peaks, and to a higher absorptance overall.

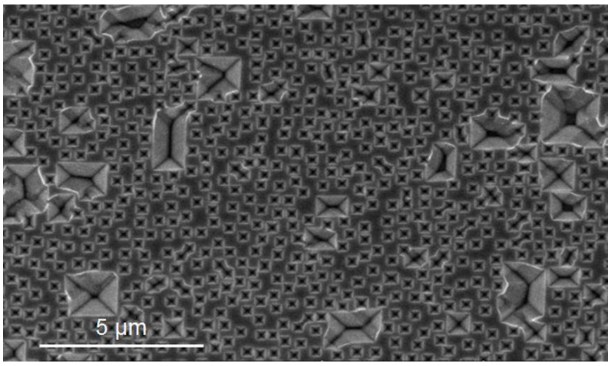


Figure 11: Pseudo-periodic HCL pattern (SEM top view showing the limitation of wet etching in disordered structures, that leads to aggregates of pyramids that destroy the optical properties [Muller2015].

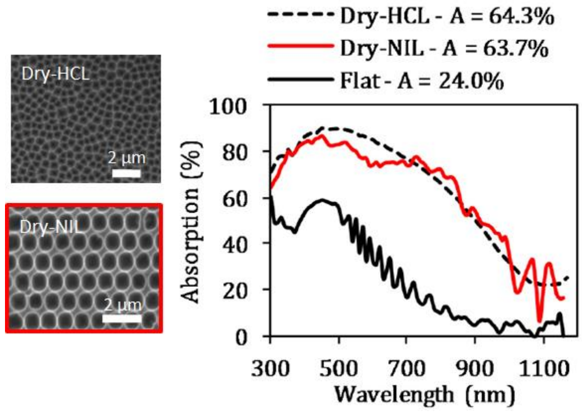


Figure 12: Absorptance of a bare 1.1 µm thin silicon foil on glass with a flat (black) or dry-etched surface patterned with NIL (red) and HCL (dotted). The disorder in the HCL pattern flattened and broadened the resonance modes visible on the NIL sample. The "A" value is absorptance integrated over the spectrum [Trom2015b].

The second goal of this nanopatterning work was to determine the electrical properties of the various fabricated nanopatterns, and to find those that combined good optical properties with good electrical properties. Many characterisation techniques were mobilised to assess the morphology and electrical properties, from standard techniques (QSSPC, AFM, SEM, TEM, etc.) to more advanced methods such as Kelvin Probe Force Microscopy, Electron Spin Resonance, Deep-level transient spectroscopy or Scanning Spreading Resistance Microscopy. With these methods, we found that transferring the pattern by dry-etching can damage significantly the electrical quality of a foil (Figure 13), which can explain the decrease in open-circuit voltage (Voc) that is often experienced with nanopatterned cells. Moreover, DLTS measurements showed that this surface damage extends deeper below the first few micrometres. Low Voc values can also be due to the steep side walls that certain nanopatterns present. Such vertical sidewalls can prevent a uniform and efficient coverage of the passivating layers on the pattern. A TEM investigation was performed in order to check the thickness uniformity of various coatings along the pattern (Figure 14). In the present case, a-Si:H, ITO, and Ti/Pd/Ag were deposited by PE-CVD, sputtering and e-beam evaporation, respectively. As expected, deeper and more vertical patterns prevent the continuity of the layers. Inverted nanopyramids present the most favourable case, where all layers are continuous (though the presence of local holes in the Pd layer could be noted). In the deepest structure, etched by RIE, the metals do not even contact the bottom of the hole and only 2-3 nm of ITO are present on the sidewalls. Continuity of a-Si:H is ensured in all cases, however its thickness also drops to a few nm only, which most probably affects its surface passivation effect. Macroscopically, the conformality of the contacting layers translates into an increase of the cell's series resistance (participating to the drop in FF, as seen in the inset table). TLM measurements confirm that the sheet resistance of the ITO-Ti/Pd/Ag stack increases significantly on a dry-etched profile, from 50 to 80 Ω/sq. This increase can be attributed to the non-conformality of the ITO rather than to the non-continuity of the metal, whose sheet resistance is not significantly affected by the voids.

In conclusion, inverted nanopyramids present excellent optical properties and are also found to be a good pattern profile to preserve the solar cell's electrical properties.

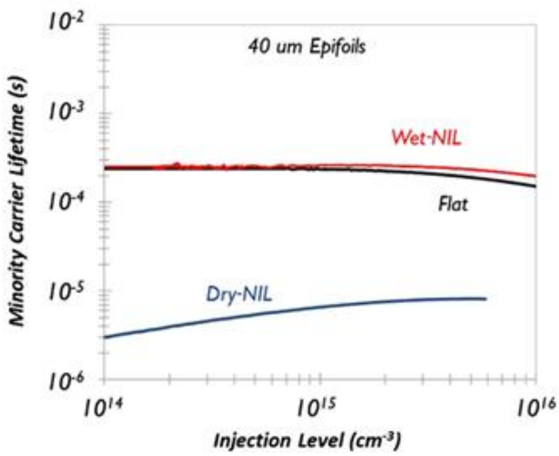
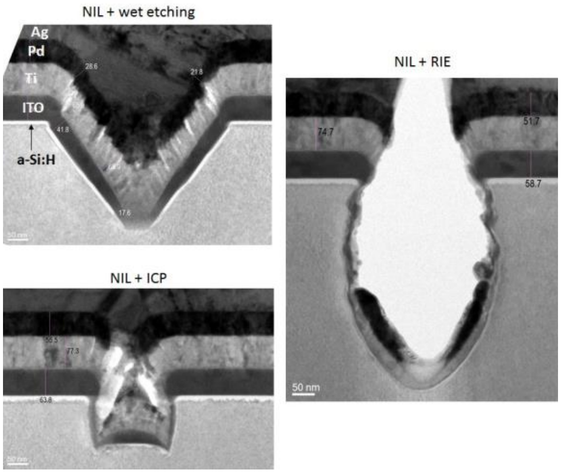


Figure 13: Minority-carrier lifetimes of flat, dry-NIL and wet-NIL textured wafers. Excellent surface passivation can be reached with wet etching [Trom2015a].



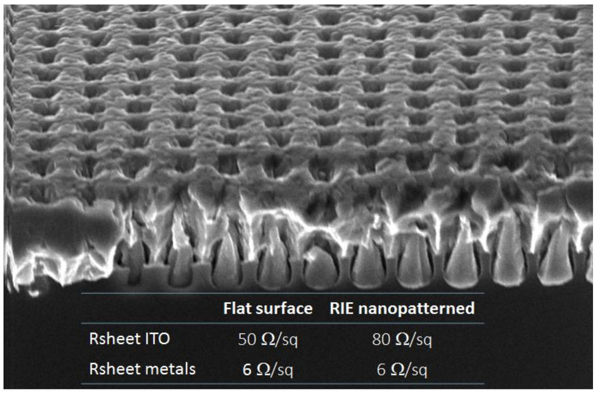


Figure 14: (left TEM of nanopatterned Si wafers with different etched profiles, showing that the thickness uniformity is affected for all materials, possibly leading to a discontinuity of the coating. (right) SEM tilted view of a dry-etched NIL pattern coated with a silver layer and the sheet resistance values (inset table) of ITO and silver on flat and nanopatterned surfaces [Depauw2014b].

Further reading

- [Trom2015a] C. Trompoukis et al., Passivation of photonic nanostructures for crystalline silicon solar cells, 10.1002/pip.2489
- I. Cosme et al., Lifetime assessment in crystalline silicon: From nanopatterned wafer to ultra-thin crystalline films for solar cells, 10.1016/j.solmat.2014.10.019
- [Trom2015b] C. Trompoukis et al., Disordered nanostructures by hole-mask colloidal lithography for advanced light trapping in silicon solar cells, 10.1364/OE.24.00A191
- C. Trompoukis et al., Photonic nanostructures for advanced light trapping in silicon solar cells: the impact of etching on the material electronic quality, 10.1002/pssr.201510394
- I. Abdo et al., Influence of periodic surface nanopatterning profiles on series resistance in thin-film crystalline silicon heterojunction solar cells, 10.1109/JPHOTOV.2015.2447831
- P. Narchi et al., Kelvin Probe Force Microscopy Study of Electric Field Homogeneity in Epitaxial Silicon Solar Cells Cross-Section, 10.4229/EUPVSEC20152015-3BO.6.1
- I. Massiot et al., Conformal bottom-up functional nanopatterns on non-planar substrates, submitted

C. Integrating nanopatterns

To fabricate thin-film crystalline-silicon solar cells, the consortium could rely on a wide panel of materials, with thicknesses ranging from 1 µm to 40 µm, with high-temperature and low-temperature growth approaches, with layer transfer from a wafer (monocrystalline silicon) or with direct growth on a foreign material (polycrystalline silicon). Four different materials were developed at IMEC and CNRS-LPICM, with the view of focusing on the best candidates step by step towards the end of the project. One should note that these c-Si cells are based on a purely crystalline material, just like wafer-based cells. It does not present any amorphous phase, like thin-film microcrystalline-silicon cells, which have different optical and electrical properties (e.g. refractive indices and minority-carrier recombination lifetime). It is thus an intermediate between the c-Si bulk technology and the amorphous and microcrystalline technology, sharing respectively their high material quality and limited thickness.

In the frame of the project, the technique for detaching low-temperature PECVD-Si foils was stabilised, leading to controlled detachment of foils with thicknesses ranging from 1.5 to 4.5 µm (Figure 15). This transfer opened the way to the possibility of processing both foil sides, hence increasing the cell efficiency potential. In parallel, new materials were developed to meet the requirements for bonding and processing on a foreign substrate. In particular, significant progress in PECVD-Si and Epifree solar cells could be achieved by replacing a-Si:H by SiOx:H, more resistant to bonding constrains.

As planned in the project strategy, three different iterations of solar cells with non-optimised and then optimised patterns were fabricated. Solar cells on all four types of materials were processed. Thanks to the interaction with the modelling and nanopatterning teams, a progressive improvement of the solar cells was possible. Figure 16 illustrates this progress on the thinnest solar cell, the 1.1-µm-thin foil transferred to glass, that ramped up to 20 mA/cm² of Jsc. This record cell may most probably still be improved both electrically and optically, by integrating inverted nanopyramids by wet-NIL rather than dry-etched HCL.

If this ultra-thin cell demonstrates the efficient integration of a nanopattern into a thin c-Si cell, its performances can however not compete with the current wafer-based cells. For this, cells with a thicker film with a minimum of 10 µm would be necessary. High-efficiency cells, above 20%, could unfortunately not be achieved in the time frame of the project. Handling issues, specific to thin-film c-Si cells would first have to be perfectly solved.

Figure 15: 1.5-µm-thick epi-PECVD silicon foil transferred to glass by anodic bonding.

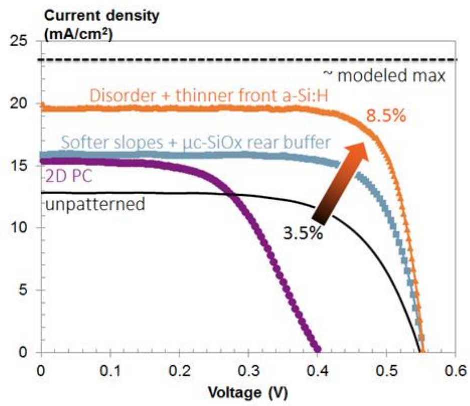


Figure 16: Progression in epifree solar cell J-V performances up to 8.5% with a dry-HCL texture.

Further reading

- [Depauw2014a] V. Depauw et al., Micrometer-thin crystalline-silicon solar cells integrating numerically optimized 2-D photonic crystals, 10.1109/JPHOTOV.2013.2286521
- I. Abdo et al., Integration of a 2D Periodic Nanopattern Into Thin Film Polycrystalline Silicon Solar Cells by Nanoimprint Lithography, 10.1109/JPHOTOV.2014.2339498
- J. Govaerts et al., Solar cells from epitaxial foils: an epifoil epiphany, 10.1016/j.egypro.2015.07.123
- R. Cariou et al., Low Temperature Epitaxial Growth of Si and SiGe and Their Transfer to Foreign Substrate, 10.4229/28thEUPVSEC2013-3DO.7.5
- W. Chen, Influence of anodic bonding on the surface passivation quality of crystalline silicon, submitted.

D. Assessing the cost of nanopatterns

One of the purposes of PhotoNVoltaics, was to assess whether nanopatterning techniques may eventually be applied in the photovoltaics field, that is whether they could meet the stringent low-cost requirements. Our industrial partner, TOTAL, with input from OBDUCAT, assessed the cost of the three nanopatterning techniques used in our consortium, LIL, NIL and HCL. Since the two last techniques are still at lab-scale, many assumptions had to be made, which prevented a quantitative comparison. Still, these cost calculations let us identify the main pathways for cost reduction of these techniques. For all three, consumables were found to represent the largest share of cost. Reduction of consumables cost and consumption, and designing higher throughput equipment, are the two main levers for reaching in the future attractive costs for nanopatterned thin-film c-Si films.

For further reading on general project results

- C. Trompoukis et al., Photonic nanostructures for advanced light trapping in thin crystalline silicon solar cells, 10.1002/pssa.201431180
- [Depauw2014b] V. Depauw et al., Nanophotonics for ultrathin crystalline silicon photovoltaics: When photons (actually) meet electrons, 10.4229/EUPVSEC20142014-3BO.6.5

Potential impact, main dissemination activities and exploitation of results

As a FET (Future Emerging Technologies) project, targeting longer-term research in a high-risk approach, the aim of PhotoNVoltaics was mainly to assess new technological routes and potentialities of new technologies, rather than leading to a direct exploitation within the PV industry. Its impact is twofold, scientific and technological. PhotoNVoltaics generated knowledge, answered scientific questions, identified paths for industrial deployment and developed specific know-how. These are being broadly disseminated and can be exploited for development in various ways.

Dissemination

Sharing its scientific and technological findings within the Photovoltaics and Photonics communities is a core mission of the PhotoNVoltaics consortium. 11 peer-reviewed journal articles have been published to date, with about 13 more (to be) submitted. The consortium strived to put them on open access and, as a result, 10 out of 11 are directly downloadable via the project website, together with 8 additional conference proceedings. To spread and discuss these results, 24 different international conferences were attended, to which 6 speakers were invited, and 2 were awarded a student prize. Future conference attendances to spread the results are planned and are regularly updated on the website. For non-specialists, an article was published in European Energy Innovation (Spring 2013) and general articles presenting the project results are planned early 2016. Finally, a dissemination kit is available for download on the project website. For updated information, please visit www.photonvoltaics.org.

Exploitation and potential impact

From its multidisciplinary approach, the knowledge and know-how that PhotoNVoltaics generated can potentially impact the fields of PV and Energy, Photonics and Nanopatterning in different ways:

1. Contribute to the establishment of a strong scientific and technical base for European science and technology in emerging areas in the energy field.

The main impact and exploitation possibilities of PhotoNVoltaics are scientific. Finding how to integrate nanopatterns into thin solar cells, without damaging their electrical properties has resulted in a deeper understanding of both optical and electrical properties of patterned surfaces in general, and for PV in particular. PhotoNVoltaics has added bricks to the fundamental understanding of surface damage and passivation, and of light in-coupling and trapping. It has resulted in the development of optical modelling tools to rigorously assess the impact of a wide range of randomness inside ordered nanostructures, with potential further licensing and use in related fields. The results are being spread within the PV and photonics communities by numerous publications on open access. The selection of the project results as a highlight of the European PV Solar Energy Conference and Exhibition in September 2015 is a direct evidence of the interest of the community.

2. Open new paths leading to highly innovative technologies for energy applications.

As an end result, PhotoNVoltaics demonstrates that by following certain guidelines, nanopatterning can be integrated as a front-side texture in a film c-Si solar cell, to efficiently trap more photons inside without compromising its electrical quality. With its extreme thinness of 1 µm (as compared to 180 µm for standard industrial wafer-based cells), that "epifree" demonstrator cell cannot compete with wafer-based cells in terms of energy-conversion efficiency. However this successful integration, and the understanding behind, open the way to applications in thin-film cells of 10-50 µm, which could then reach efficiencies well beyond 20%. The project is thus opening the way for such light management developments in the PV community. Furthermore, by assessing the cost of nanopatterning, we have identified the pathways for a future deployment into the PV industry, shedding light on its conditions. In parallel, if the purpose was here limited to photovoltaics, alternative applications have emerged from the developed nanopatterning techniques (e.g. for nanowire array growth), and they may benefit to other fields where light management is involved, such as photodetectors or photochemistry. Finally, next to its targets for light management, PhotoNVoltaics has led to "side-effect" developments, such as lift-off of low-temperature grown c-Si films or handling of flexible and fragile silicon films.

3. Impact the energy system.

Enabling thin-film crystalline-silicon solar cells, by converting micron-thin films into highly-efficient sunlight converters, would enable a new generation of modules that would be a breakthrough in terms of material/energy/CO_2 emissions and financial savings. A solar cell of 40 µm, with re-use of its parent wafer, would decrease the silicon consumption by a factor 5 to 30. Furthermore, depending on the methods for producing these foils, low-thermal budget routes may be followed for solar cell fabrication, further lowering the cost, and even opening the way to plastic carriers for flexible modules. Finally thin-film cells would be processed all together, monolithically, on their carrier substrate that will eventually be the module, leading to a significant simplification of the final product, similarly to traditional thin-film technologies. So far however, it must be noted that the PV industry has kept postponing the integration of thinner wafers and the lower cost of polysilicon nowadays has decreased the incentives for thinner cells since the beginning of the project. Still, a few companies are currently emerging to exploit the potential of the concept of kerfless silicon cells. Nanopatterning would enable further gains in thickness of silicon and cell efficiency by boosting the cell's short circuit current beyond what is currently obtained with random pyramids. Moreover, the nano-texture itself would help minimizing the material waste, by consuming only a few hundreds of nanometres of silicon, as opposed to the few micrometres lost today. It would also increase the module energy yield by providing it with a large angular robustness to illumination. Interestingly, the latter two advantages may already benefit to today's wafer-based cell technology. However, these impacts depend whether the nanopatterning industry may provide industrial tools that meet specific requirements that the consortium underlined, in particular the need for significantly minimised amounts of consumables and higher throughputs to meet 3000 wafers per hour.

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