Energiteknologisk udvikling og demonstration

EUDP 64016-0030

BLACK SILICON BIPV – PHASE 2

Cost and energy effective all-black solar panel for building integration with maximum aesthetic value

FINAL REPORT

Title:
BLACK SILICON BIPV – PHASE 2
Cost and energy effective all-black solar panel for building integration with maximum aesthetic value

EUDP Project number
64016-0030

Project Partners
DTU Fotonik (Project Manager)
DTU Nanotech
IPU
Nines PV
SoliTek
Kompromet (replacing Gaia Solar November 2017)
Gaia Solar (until May 2017)

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December 2019

Front page
Image of black silicon textured solar cells by NinesPV and strings treated selectively by IPU implemented in PV module (by SoliTek) in a Kompromet slate façade system.

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1.1 Project details

Project title	Black Silicon BIPV – Phase 2 - Cost and energy effective all-black solar panel for building integration with maximum aesthetic value
Project identification (program abbrev. and file)	Journalnr.: 64016-0030
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	DTU Fotonik, Frederiksborgvej 399, 4000 Roskilde
Project partners	DTU Nanotech Komproment (replacing Gaia Solar November 2017) IPU NinesPV Solitek
CVR (central business register)	30060946
Date for submission	31-12-2019

1.2 Short description of project objective and results

English

The objective of the project has been to develop and manufacture a novel type of solar panel based on a new type of solar cell (black silicon solar cell), which – apart from a high and preferably improved efficiency and an implementable and cheaper production method – should have several significant advantages in terms of building integration.

The tabbing wires interconnecting the cells in the panel has been processed into non-reflecting black strings in a scalable, inorganic electrochemical process step securing a completely black appearance of the solar panel later produced.

Machinery for making the strings black automatically has been developed and is on the verge of being industrialized. The processes are compatible with the standard panel production process of traditional PV panels. A total black silicon BIPV module is demonstrated based on one of the concepts in Komproment's product catalogue. The project has during the project period achieved:

- Development of black electroplating methods to make the front metal busbars black
- Development of a machine to automatically process the strings to selectively dyed
- Design and production of Black Silicon cells with black busbars
- Manufacturing of a demonstrator module fitting in Komproment's product catalogue
- Reliability test of black silicon treated cells and the chemically processed busbars in the panel

A patent has been filed on the technologies for protection in the post project commercialization phase. The objective of the project has been met though some life-time issues has to be solved. Further investment has been attracted to investigate these issues in 2019.

Dansk

Formålet med projektet har været at udvikle og fremstille en ny type solcellepanel baseret på en ny type solcelle (black silicon), som – udover høj og forbedret effektivitet samt implementerbar og billigere produktionsmetode – har adskillige væsentlige fordele med hensyn til bygningsintegration.

De elektriske ledere (strenge), der forbinder cellerne i panelet, behandles til ikke-reflekterende sorte strenge i et skalerbart, uorganisk elektrokemisk procestrin, der sikrer et fuldstændigt matsort sort udseende af det senere producerede solcellepanel.

Maskiner til automatisk at gøre strengene sorte er blevet udviklet og forestår af at blive industrialiseret. Processerne er kompatible med standardpanelproduktionsprocessen for traditionelle PV-paneler. Et samlet sort silicium BIPV-modul er blevet demonstreret på basis af et af koncepterne i Komproments produktkatalog. Projektet har i projektperioden opnået:

- Udvikling af sorte elektropletteringsmetoder til farvning af strenge til solpaneler
- Udvikling af en maskine til automatisk at behandle strengene til selektiv farvning
- Design og produktion af sorte siliciumceller med sorte strenge
- Fremstilling af et demonstratormodul, der er kompatibelt med facadesystem i Kompromentss produktkatalog
- Pålidelighedstest af sorte siliciumbehandlede celler og de kemisk behandlede loddestrenge i panelet

Der er indgivet patent på teknologier til beskyttelse i den efterfølgende kommercialiseringsfase. Målet med projektet er opfyldt, dog er identificeret nogle problemer med levetider. Yderligere investeringer er tiltrukket til at adressere disse udfordringer i 2019.

1.3 Executive summary

This project is an extension of the project EUDP J. No. 64015-0006 Black Silicon BIPV, where a proof of concept mini-module was demonstrated based on black silicon with black strings generated by a chemical oxidation. Here prototypes with black silicon and black strings was successfully made with the same performance as conventional technology.

The objective of the project has been to develop and manufacture a novel type of solar panel based on a new type of solar cell (black silicon solar cell), which – apart from a high and preferably improved efficiency and an implementable and cheaper production method – should have several significant advantages in terms of building integration.

The tabbing wires interconnecting the cells in the panel has been processed into non-reflecting black strings in a scalable, inorganic electrochemical process step securing a completely black appearance of the solar panel later produced.

Machinery for making the strings black automatically has been developed and is on the verge of being industrialized. The processes are compatible with the standard panel production process of traditional PV panels. A total black silicon BIPV module is demonstrated based on one of the concepts in Komproment's product catalogue. The project has during the project period achieved:

- Development of black electroplating methods to make the front metal busbars black
- Development of a machine to automatically process the strings to selectively dyed
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- Manufacturing of a demonstrator module fitting in Komproment's product catalogue
- Reliability test of black silicon treated cells and the chemically processed busbars in the panel

A patent has been filed on the technologies for protection in the post project commercialization phase. The patent is owned 50% by DTU and 50% by IPU, and a proof-of-concept (PoC) investment of 500kkr. has been attracted to investigate the commercialization of the machine after the end of the EUDP project addressed in this report.

The project ends at TRL level 7, and the involved companies cannot implement the technologies before higher TRL levels are reached and the investment above will deal with especially the stringing machinery, that is the major innovation in this project that potentially can lead to

- A new company producing the machines
- A company transferring knowledge to machine producers for the PV industry addressing especially the string producers
- License sale

The research has benefitted heavily the new Study Line within Solar Energy that DTU Fotonik has been leading the creation of while this project has been ongoing. It was announced in 2017 and launched in September 2018 with great success. The study line consists of many new photovoltaics courses and one dedicated to building integrated photovoltaics. This EUDP project has been used as a corner stone for teaching students in new innovative ways of addressing the needs from architects and other stakeholders concerned with aesthetics of the building envelope. New technologies are needed to meet the demands and there is a great opportunity now to create new products serving this market while supporting the transformation towards a sustainable energy production. The large interest from Danish industry in building integrated photovoltaics has further led DTU to investment in a R&D facility at DTU Fotonik at Risø Campus in Roskilde where new concepts of BIPV solutions can be fabricated and tested. This facility also serves as hands-on teaching of DTU students and industry on fabrication of BIPV solutions. The facility was opened August 2019.

1.4 Project objectives

This project is an extension of the project EUDP J. No. 64015-0006 Black Silicon BIPV, where a proof of concept mini-module was demonstrated based on black silicon with black strings generated by a chemical oxidation. Within the above project we succeeded making prototypes with black silicon and black strings with the same performance as conventional technology, and we have furthermore initiated a patent process, which has led to filing of a patent in the successor project which the rest of this report addresses.

The objective of this EUDP project (64016-0030) has been to develop and manufacture a novel type of solar panel based on a new type of solar cell (black silicon solar cell), which – apart from a high and preferably improved efficiency and an implementable and cheaper production method – should have several significant advantages in terms of building integration. The tabbing wires interconnecting the cells in the panel has been processed into non-reflecting black strings in a scalable, inorganic electrochemical process step securing a completely black appearance of the solar panel later produced. Machinery for making the strings black automatically has been developed and is on the verge of being industrialized. The processes are compatible with the standard panel production process of traditional PV panels. A total black silicon BIPV module is demonstrated based on one of the concepts in Komproment's product catalogue.

The major activities in the project have been:

- Investigation of interconnection method and choice of interconnection strategy
- Development of black electroplating methods to make the front metal busbars black
- Design and production of Black Silicon cells with black busbars
- Development and demonstration of a module technology supporting the all black silicon cell
- Development of a cost-effective direct process yielding black busbar strings for cell interconnection
- Development of a Black Silicon solar cell module that supports the developed metallization process
- Secure electrical contact to the black busbar strings
- Design and specification of a flexible module production method for the all-black solar cell
- Manufacturing of a demonstrator module fitting in Komproment's product catalogue
- Reliability of black silicon treated cells and the chemically processed busbars in the panel
- Investigation of commercialization of colored PV panels and the machinery for dyeing the strings black.

The project started out with the following partners, DTU Fotonik (project manager), DTU Nanotech, IPU, SoliTek, FillFactory and Gaia Solar. FillFactory needed to leave already before the project started due to insecurity of the company's long-term financial situation. NinesPV replaced FillFactory bringing in their automatic Si-texturing pilot line which are being industrialized in parallel with this project. Gaia Solar went bankrupt in the middle of 2017 and was replaced by Komproment. Especially the last partner change was troublesome since the curators controlling the remains after Gaia Solar was non-responsive and at least half a year was lost before the activities was transferred to Komproment. Despite these unforeseen obstacles the partners had an excellent collaboration in the project that commercially has led to a patent application and development of machinery which is in the process of commercialization.

1.5 Project results and dissemination of results

A detailed description of the main activities and technical results in the project as well as description of commercial results and expectations of the project are given below.

Black silicon treatment of the PV cells

The texturing of silicon leading to the black appearance of the solar cells was performed using advanced physical etching methods such as Atmospheric Dry Etch (ADE) and Reactive Ion Etch (RIE), by NinesPV and DTU Nanotech respectively. These texturing methods lead to almost completely suppressed reflectance of light at the air-silicon interface and thus darker appearance as compared to surface textured with conventional wet etch methods. NinesPV, DTU Nanotech and Solitek worked in tight collaboration to ensure compatibility of the silicon surfaces textured using ADE and RIE with the standard process flow and equipment of Solitek. In particular, modified recipes for pre-and post-ADE or RIE were developed. In addition, minor adjustments in some fabrication parameters of solar cells were implemented by Solitek.

DTU Nanotech worked further in order to explore advanced passivation schemes for silicon surfaces textured using RIE. In particular, replacing the standard front surface passivation layer of hydrogenated silicon nitride (SiN_x:H) with aluminum oxide (Al_2O_3) or with Al_2O_3/ SiN_x:H stacks. The latter ones are increasingly relevant for industrial application and are currently being used in *e.g.* high efficiency Passivated Emitter and Rear Contact (PERC) cells. In addition, DTU Nanotech led exploratory work to understand in more detail the physical/electrical properties of black silicon fabricated by ADE and RIE etching methods. The main goal was to minimize the damage induced at and below the silicon surface, thus resulting in lower losses due to surface recombination and therefore higher cell voltage.

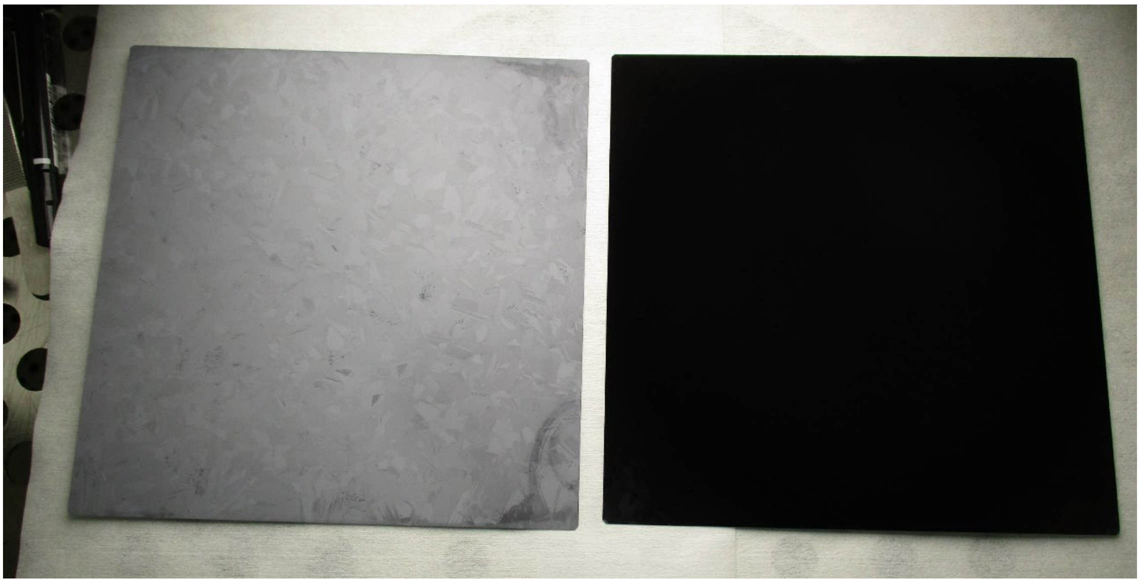


Fig. 1: Left: Raw silicon wafer, right RIE etched wafer.

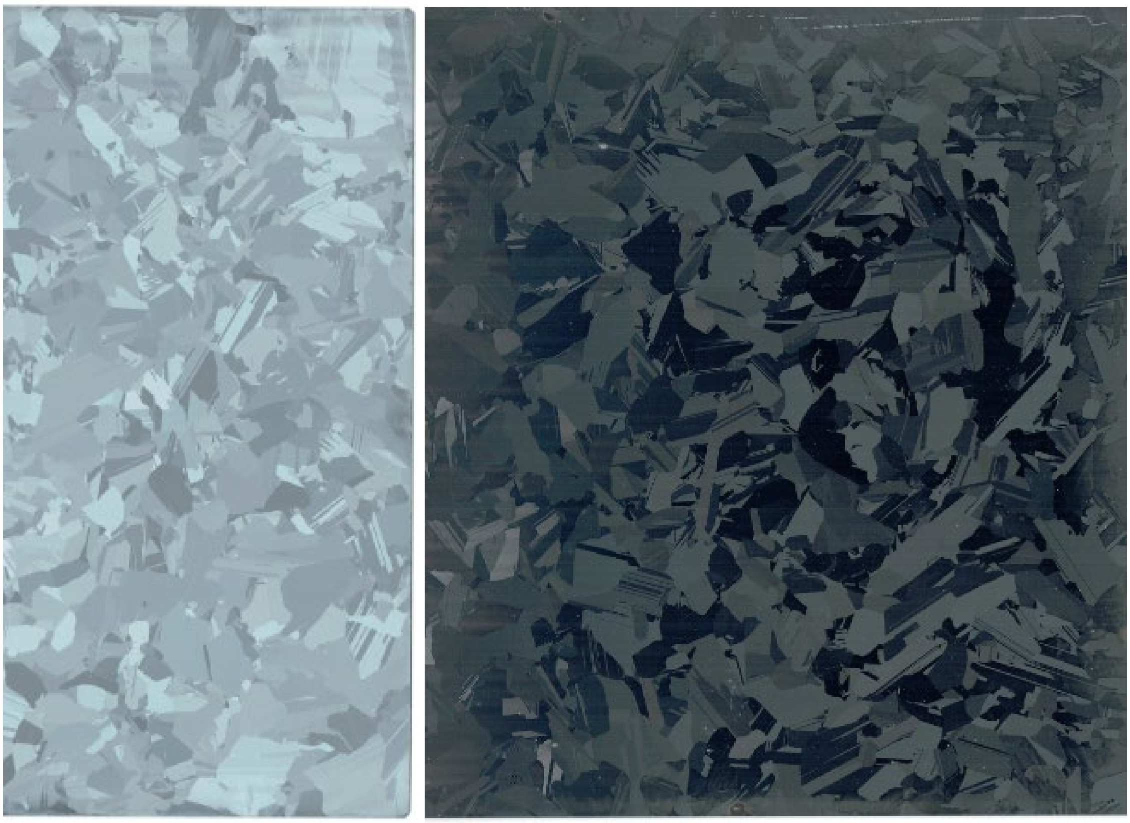


Fig. 2: Left: Raw silicon wafer, right: ADE treated wafer.

Black coating on ribbons

During phase 1 of the Black Silicon, black coatings for the bus-bar ribbons, such as CuO and NiZnS were investigated. However, NiZnS gives rise to bobble generation during lamination (as shown in Fig. 3), and since problems with electrical contact of the bare copper ribbons with black oxide surface to the silver lanes could not be solved using conductive glue, the black coating tests were continued during phase 2 of the project in order to investigate other options.

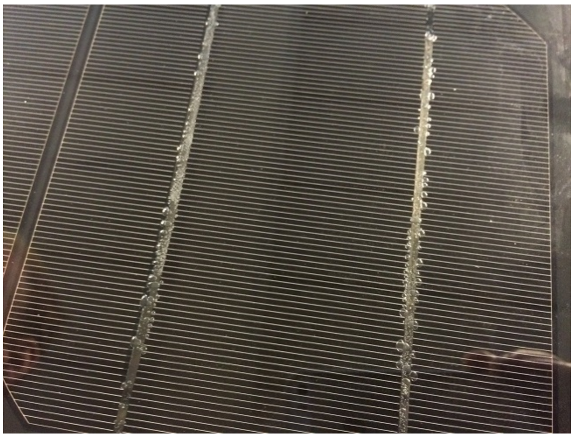


Fig. 3: Laminated solar cells with NiZnS coated ribbons.

Exchange deposition of copper was investigated as an alternative way for blackening ribbons. Direct exchange deposition of copper on ribbons with solder does not provide sufficient black color, while the introduction of a zinc intermediate layer has a low reflection similar to what was obtained with NiZnS (see Fig42). Lamination test shows that this Zn/Cu coating also perform very well during the lamination process and keeps a good black color (middle string in Fig.5). The blackening process now has two deposition steps, however; both of them take only a very short time of 15-30 seconds.

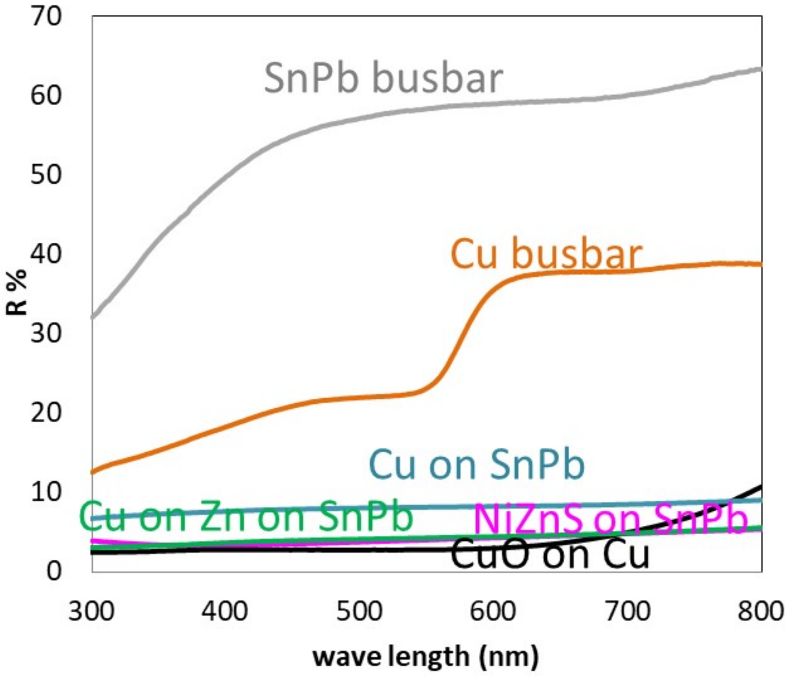


Fig. 4: Reflectance of various bus-bars (ribbons) and black coatings.

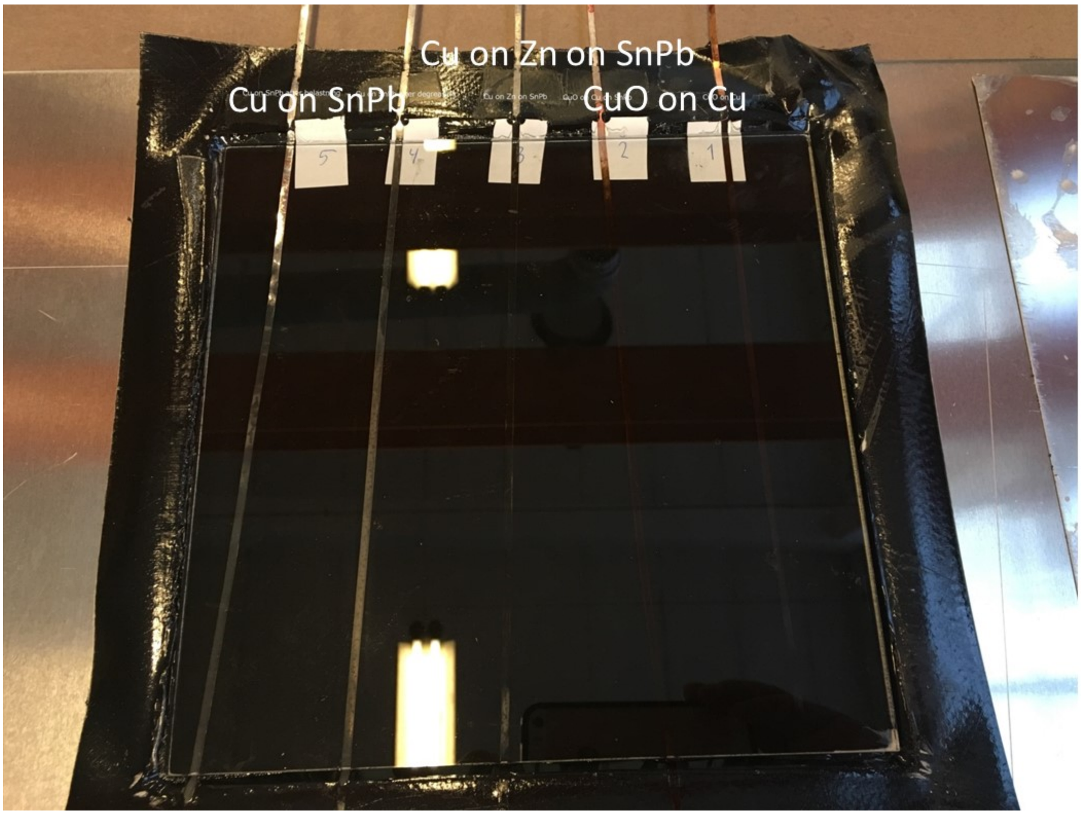


Fig. 5: Photo of laminating test with Cu on SnPb (solder) two most left), Cu on Zn on SnPb (middle) and CuO and bare Cu (two string most right).

Pretreatment of ribbons

The various pretreatment processes were investigated by comparing the adhesion of coating to surface of the ribbon (bus-bar) using the so-called tape test. Fig 6. shows the reflectance of Cu/Zn coated bus-bar with applied degreasing, blasting and chemical pretreatments before the zinc (Zn) electroplating step - after the tape test. Low reflectance indicates that the blackening surface is undisturbed by the tape test, while a higher value indicate that some of the black coating has been removed by the tape. Pretreatment in 0,4M HCl gives a good adhesion of the coating to the solder surface – similar to the adhesion obtained by blasting ("blæsning").

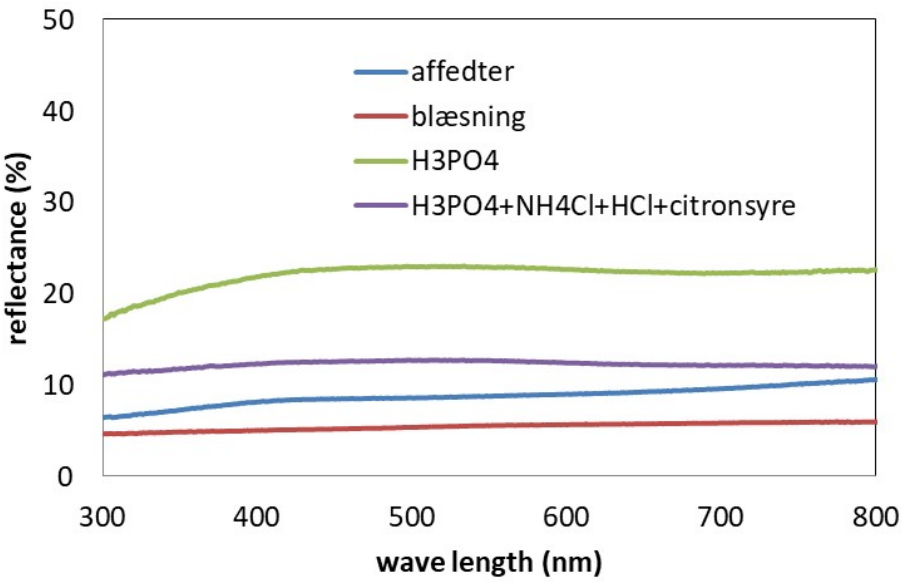


Fig. 6: Reflectance of Zn/Cu coated bus-bar with different applied pretreatments after tape test.

Selective coating

A process for selective blackening was developed in order to enable soldering at the back side of bus-bar ribbon. The selective coating can be obtained by removing the black coating from certain areas of the ribbon or by preventing the deposition of the coating in those areas. Since preventing the coating from being deposited is relatively complex to establish – it will require some kind of masking or photoresist – it was decided to remove the coating at the surface where soldering should take place.

Quick blasting tests were made using a small mechanical set-up (Fig. 7), which allowed for adjustment of the distance and angle between the jet flow and the sample surface. Also the exposure time were varied.

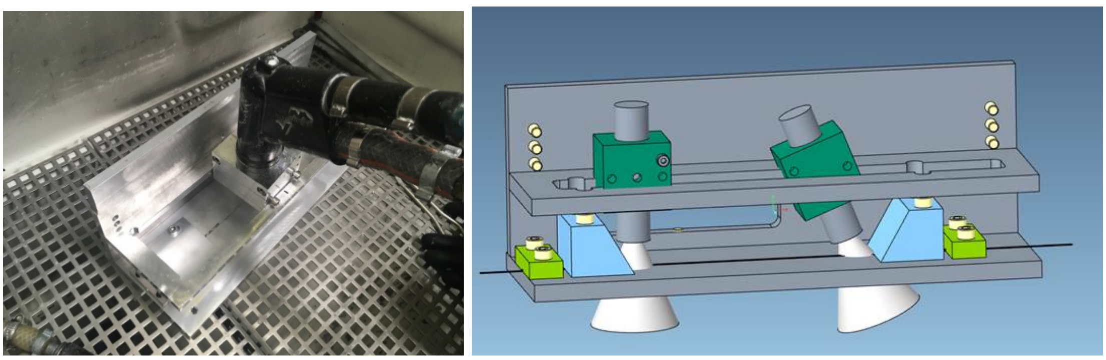


Fig. 7 Photo and drawing of set-up for quick test of blasting

Fig. 8 shows a photo of a bus-bar sample after a quick blasting test and under that a XRF profile which measures the intensity of Sn and Zn as a function of distance. The sample was exposed to the blasting gun in a window of 10 cm in width. The profiles indicate that the Zn coating is removed while the solder material (represented by Sn) remains in the areas where the surface is exposure to blasting. Blasting after blackening could be a way to obtain selective coating.

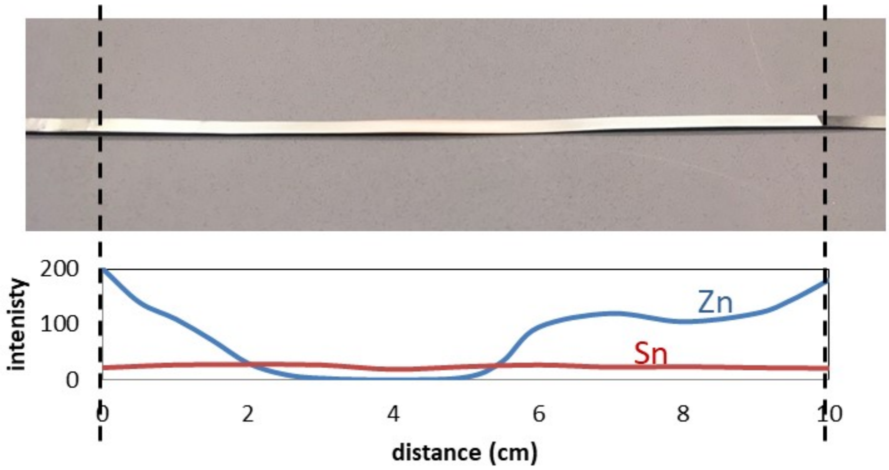


Fig. 8: Photo of bus-bar sample after blasting quick test and XRF profiles for Zn and Sn as a function of distance. The moving speed of the blasting gun was not constant.

Construction of prototype machine for selective coating of ribbons
The necessary equipment for performing the entire process for blackening of the ribbons with pretreatment, zinc electroplating, copper exchange deposition and blasting was designed, as shown in Fig. 9.

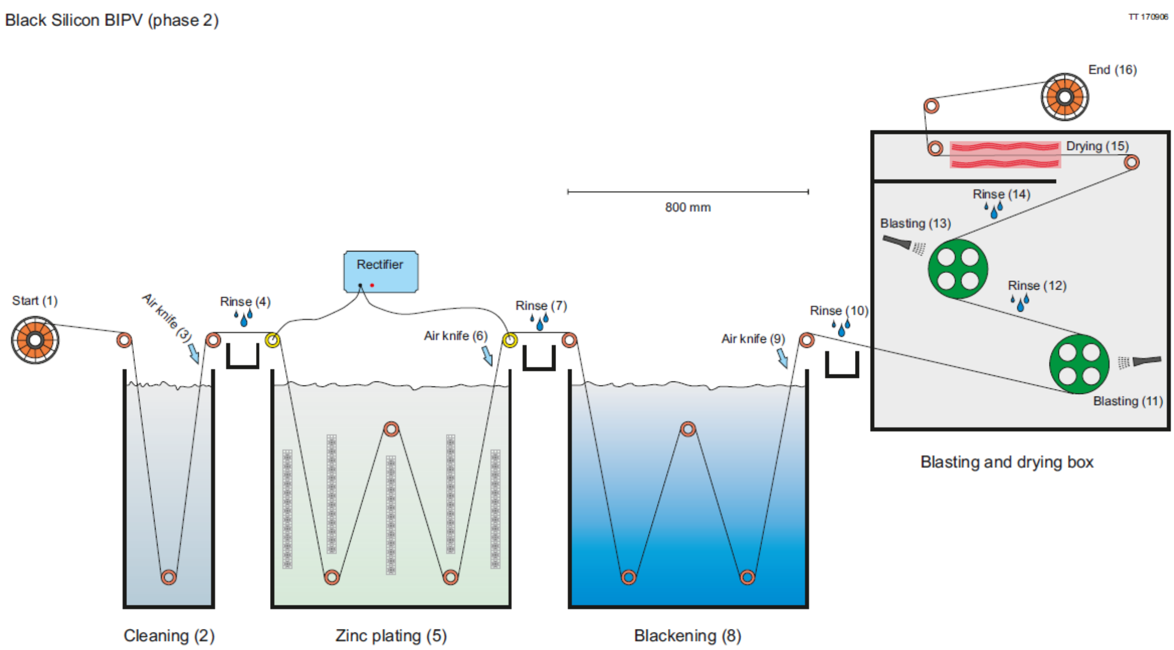


Fig. 9: Drawing of process for blackening of busbar ribbons.

The blasting machine was built (Fig.10) using a commercially available powder blasting gun (small photo to the left in fig. 10) placed in two chambers (one box for the front side and one box for the back side). The blasting powder is stored in the box on the floor in the top drawing of fig. 10. The ribbon is running through the two blasting chambers, and it either exposed to the blasting gun or not – depending on a moveable screen. The blasting powder is removed with an industrial vacuum cleaner and reused.

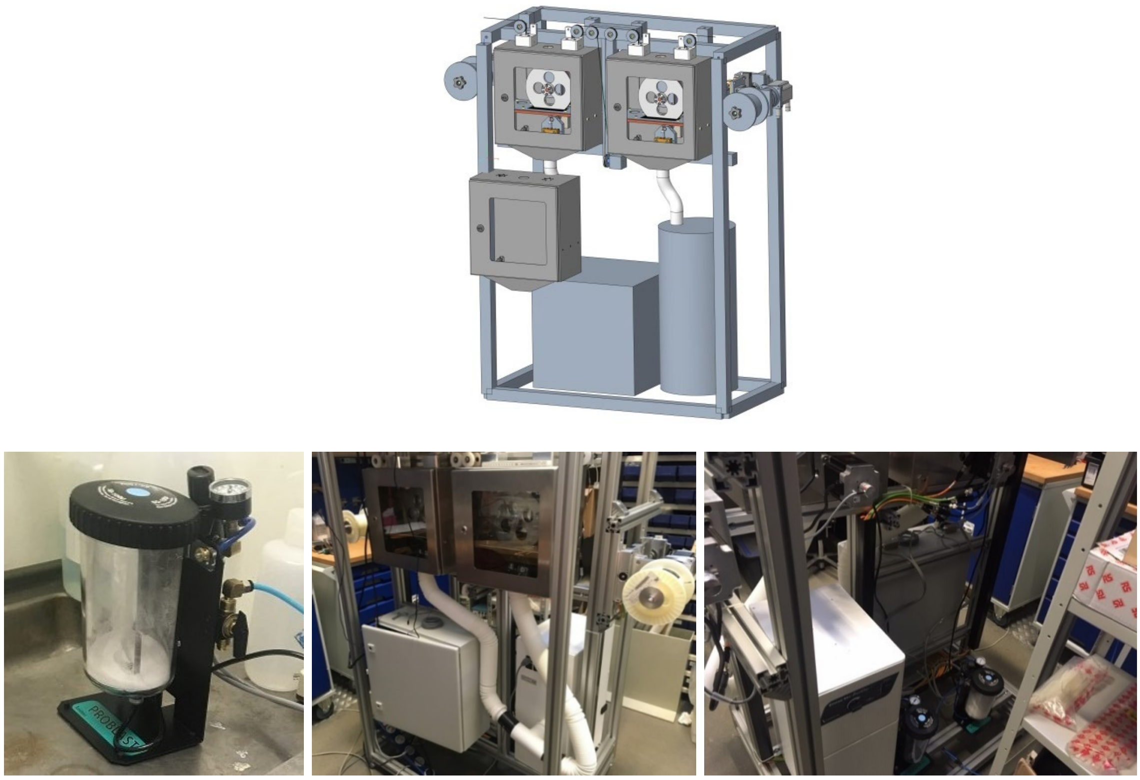


Fig. 10: Drawing and photos of the blasting machine.

Performance and Reliability

DTU Fotonik has characterized the performance and reliability of atmospherically dry etched (ADE) multi crystalline silicon from Nines, and reactive ion etched (RIE) mono crystalline silicon from DTU Nanotech. The ADE and RIE black silicon cells were turned into laminated coupons/mini modules at Solitek (see below).

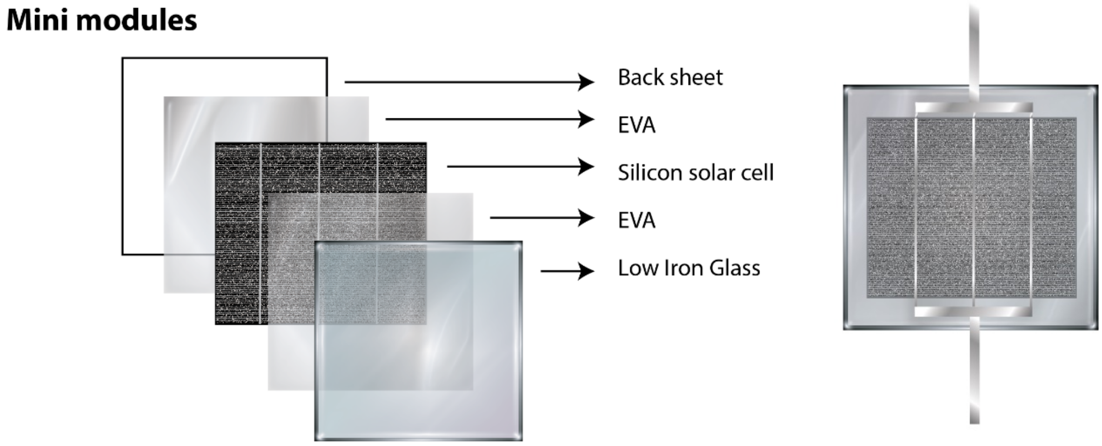


Fig. 11.: The performance tests was done on mini modules containing only 1 solar cell instead of 60 which is standard for a PV module. The composition is though exactly similar to a normal PV module.

All characterizations were done in comparison to a standard mono crystalline sample because this technology type represents roughly 90% of the current PV market. All samples tested were 6” single cells.

Photovoltaic field performance is primarily driven by the following environmental conditions: light intensity, spectral distribution of light, cell temperature, and the position of the sun (i.e. angular orientation to PV). DTU Fotonik has characterized how black silicon responds to all four of these variables because these data are essential in understanding how much black silicon energy will produce in different geographical locations.

The I-V measurements of all three samples at multiple irradiance levels are shown below. The various irradiance levels tested cover all of the meaningful light intensity levels that are observed on Earth. We see that the RIE b-si sample generates only about 90% of the photocurrent that the ADE or standard samples generate.

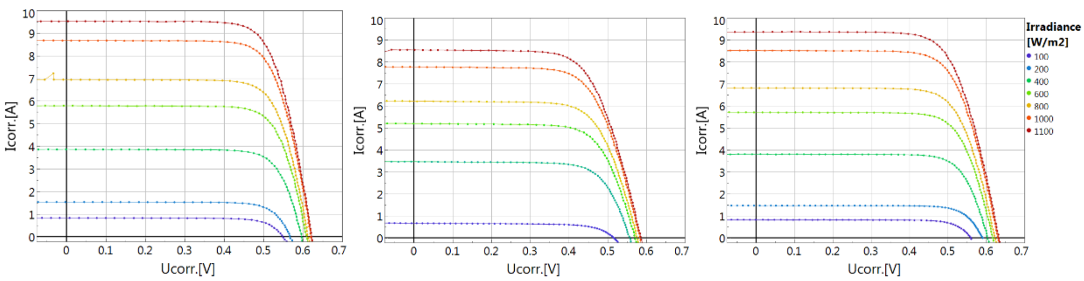


Fig. 12: Multi-irradiance I-V measured on ADE b-si (left), RIE b-si (center), and standard c-Si (right).

Table 1: Summary of I-V characteristics at standard test conditions (STC).

Test Sample	Irradiance [W/m2]	Isc (A)	Voc (V)	Imp (A)	Vmp (V)	Pmp (W)	Efficiency (%)	Fill Factor (%)
Standard c-Si	1000	8.51	0.63	7.88	0.48	3.76	15.4	70.0
RIE b-Si	1000	7.77	0.58	7.11	0.43	3.03	12.4	66.8
ADE b-Si	1000	8.67	0.62	8.07	0.49	3.90	16.0	72.6

The performance at variable temperature is shown below. Although the temperatures tested here do not span all possible cell temperatures expected in the field, the data is sufficient to fit a least squares regression to an extract what is known as the temperature coefficient. The temperature coefficients are summarized in the table below. The results show a slightly better temperature coefficient (i.e. lower in absolute terms) for the ADE sample than for the RIE or standard sample.

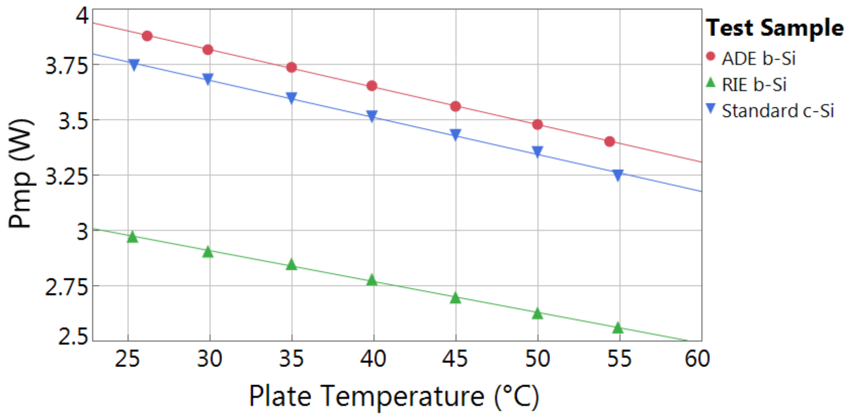


Fig. 13: Regressions of test sample power at the maximum power point (Pmp) as a function of cell temperature for three samples tested.

Table 2: the slope of the regression lines shown in the figure above relative to power at 25°C.

Sample Type	**Temperature Coefficient for Pmp [%/C]**
Standard c-Si	-0.45
RIE b-Si	-0.47
ADE b-Si	-0.44

The sun's distance relative to a stationary location will change throughout the day. This causes a continuous change in the spectral distribution of light incident on a PV panel. Furthermore, photovoltaic devices are spectrally sensitive and therefore their electrical response to different wavelengths of light needs to be understood. DTU Fotonik collaborated with the national metrology institute of Germany (PTB) to perform the needed spectral response (SR) measurements.

The measurements were performed by DTU Fotonik PhD student Mekbib Amdemeskel and are shown below. These SR data provide additional insight as to where the electrical performance of the RIE sample is lower. For example, the poor response in the shorter wavelengths indicates issues with the passivating layer, while a poor response in the longer wavelengths indicates that there could be unwanted recombination in the bulk layer.

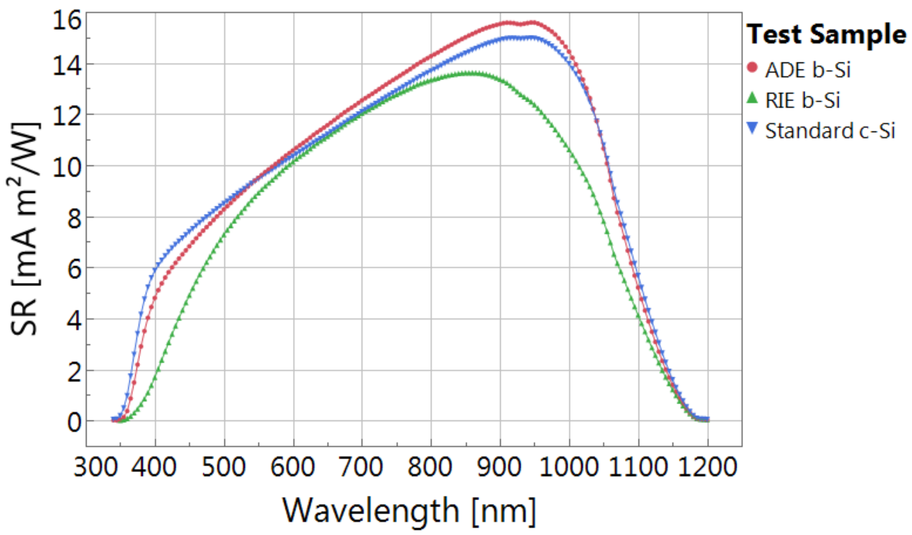
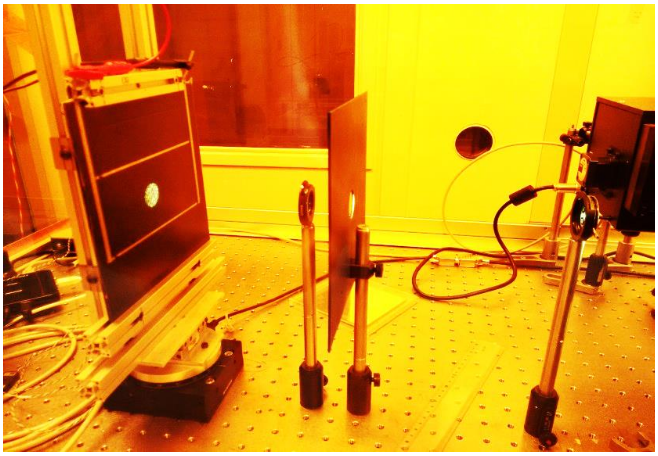


Fig. 14: Spectral response of the three samples tested.

Unless dual axis tracking is used, the angle of incidence between a solar panel and the sun will change throughout the day and over the year. An increasing amount of reflection is observed when the sun's angle relative to the normal from the PV panel's surface is greater than 45°. PV manufacturers go to great lengths to minimize this reflection by using anti-reflective coatings (ARC) and/or textured glasses. The micro/nano structures of black silicon have the potential to decrease these reflection losses beyond what is possible with the random pyramid structure on standard c-Si cells. To assess if there is are improved light trapping capabilities of black silicon, DTU Fotonik modified and improved an existing test platform. This system shown below consists of a steady state light source, filters, collimation optics and a rotational stage that can move the sample between ±90°.



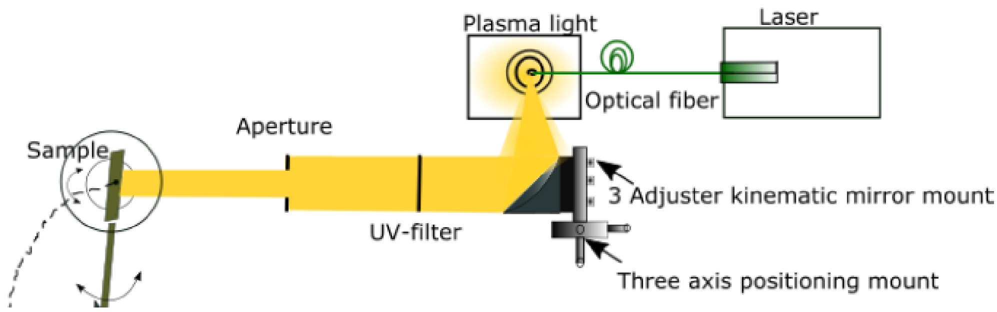


Fig. 15: Improved system for measuring the angular dependent response of solar cells.

DTU also invited seven reputable European PV laboratories to measure the angular dependence of the ADE b-Si, RIE b-Si, and standard c-Si cells. This work was the world's first ever round-robin on angular dependent measurements of solar cells. We found that five of the eight participating labs reported measurements with unacceptable deviations when the measurement was greater than 45 degrees[1]. This work was an important contribution to revise the IEC standard for performing such measurements. The full data set was published in the 35th EU PVSEC, but the DTU Fotonik measurements on the three samples are shown below. The y-axis is the incident angle modifier (IAM), which is a ratio of how much direct beam light was received and used by the cell, divided by the light that was available to the cell. The zoomed figure shows that at best the ADE b-Si shows a 1% gain in angular response relative to the RIE b-Si and Standard c-Si samples. However, this difference is well inside the uncertainty bars and could easily be due to an artifact. All three cells were laminated with the same type of front glass and there for it is no surprise that they all perform identically since it has been shown that the glass-air interface dominates the angular response.

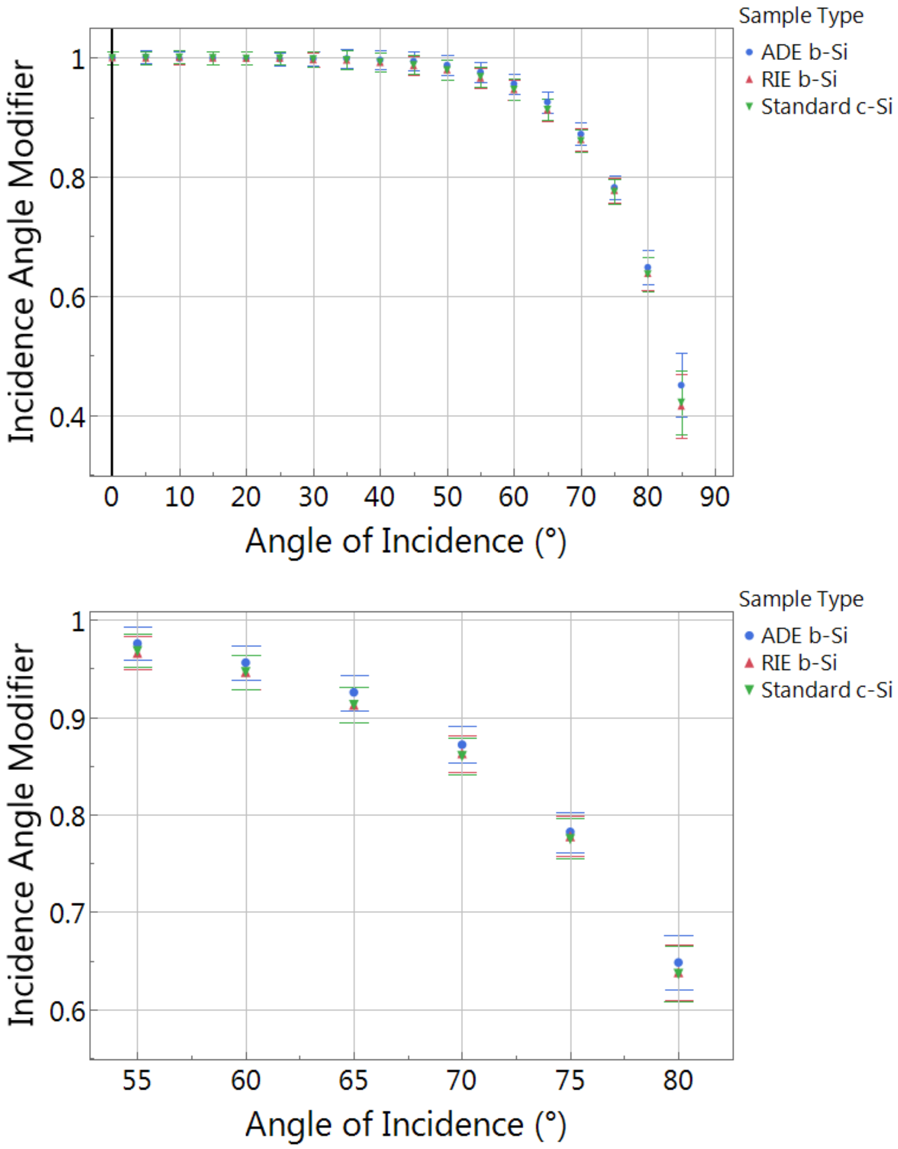


Fig. 16: The angular response shown as the incidence angle modifier as a function of angle (top) and the same data but zoomed into 55° to 80°.

[1] DTU was not one of these five labs!

Reliability is crucial for protecting the downstream consumers of PV and for increasing investor confidence. PV panels are expected to last 25+ years in the field and black silicon should be no exception to this rule. Rather than waiting for 25 years of field data, it is more practical to perform accelerated stress tests in the lab to gauge PV reliability. To this end, DTU Fotonik has built an accelerated stress testing platform to investigate black silicon's susceptibility to one of the most frequently occurring failure modes – Potential Induced Degradation (PID). As the name implies, PID is a degradation mode that occurs when PV cells are wired high voltage (i.e. high potential) strings. DTU Fotonik has built the box shown below to simulate such a high voltage mounting situation. A high voltage of 1000-1500VDC is applied to the cells and the degradation mechanism (leakage current) is monitored for four to eight days. Up to 12 samples can be tested simultaneously.

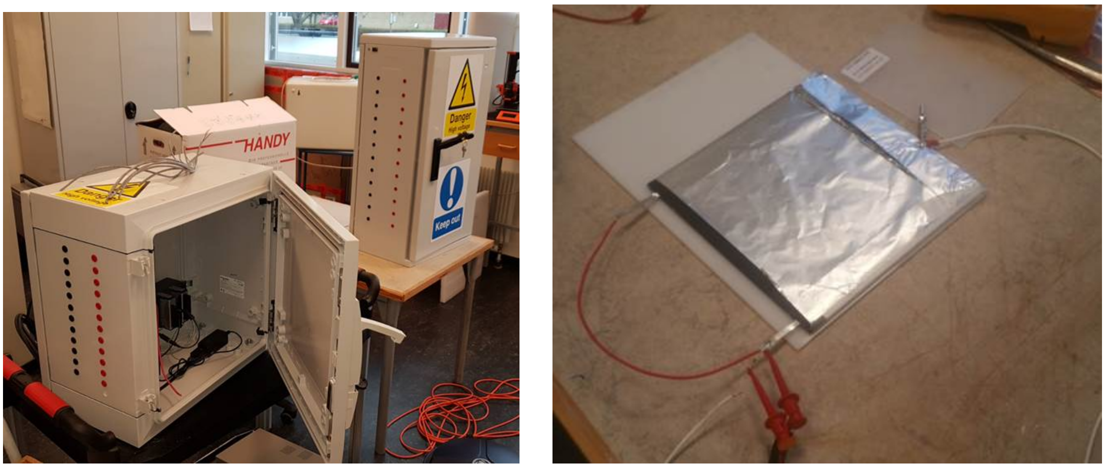


Fig. 17: Enclosures for high voltage power supply, sensing resistors, and test samples (left). Example of test sample wrapped in conductive foil to activate leakage current (right).

Two samples of black silicon treated silicon solar cells was tested ~500 hour PID tests @1000V (negative bias) were laminated with low cure time (~6min). 500 hours is > 2x the recommended time by the standard. STC and EL was done before and after. The data show that no degradation occurred from PID. The variability chart below shows a summary of the IV data.

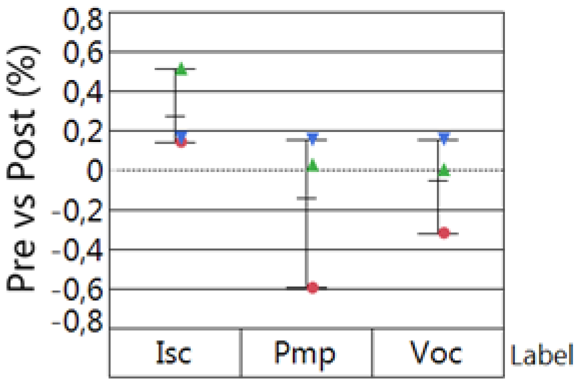


Fig. 18: PID test of 2 samples of black silicon treated solar cells (RIE and ADE).

Leakage current during the test was always < 30nA which is within the range of being PID resistant.

5 mini modules with bus-bars made black by IPU was chosen for thermal cycling test. The process is shown below.

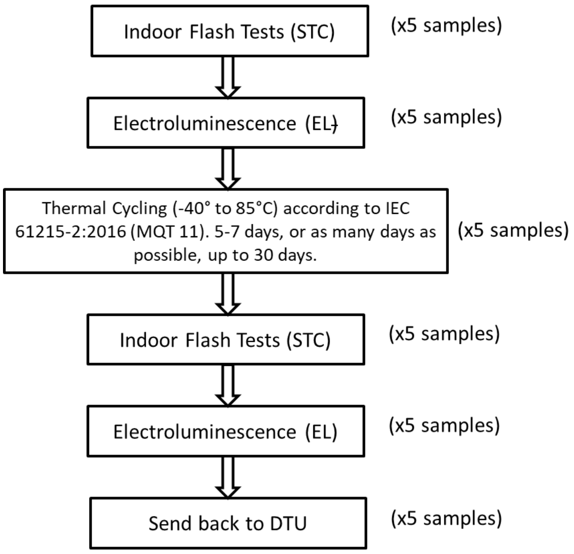


Fig. 19. Thermal cycling test of 5 mini-modules with black busbars.

The samples were flash tested and EL was done in DTU Fotonik in Roskilde, and thermal cycling was done at University of Cyprus (UCY). A photo of the samples in the chamber can be seen below:

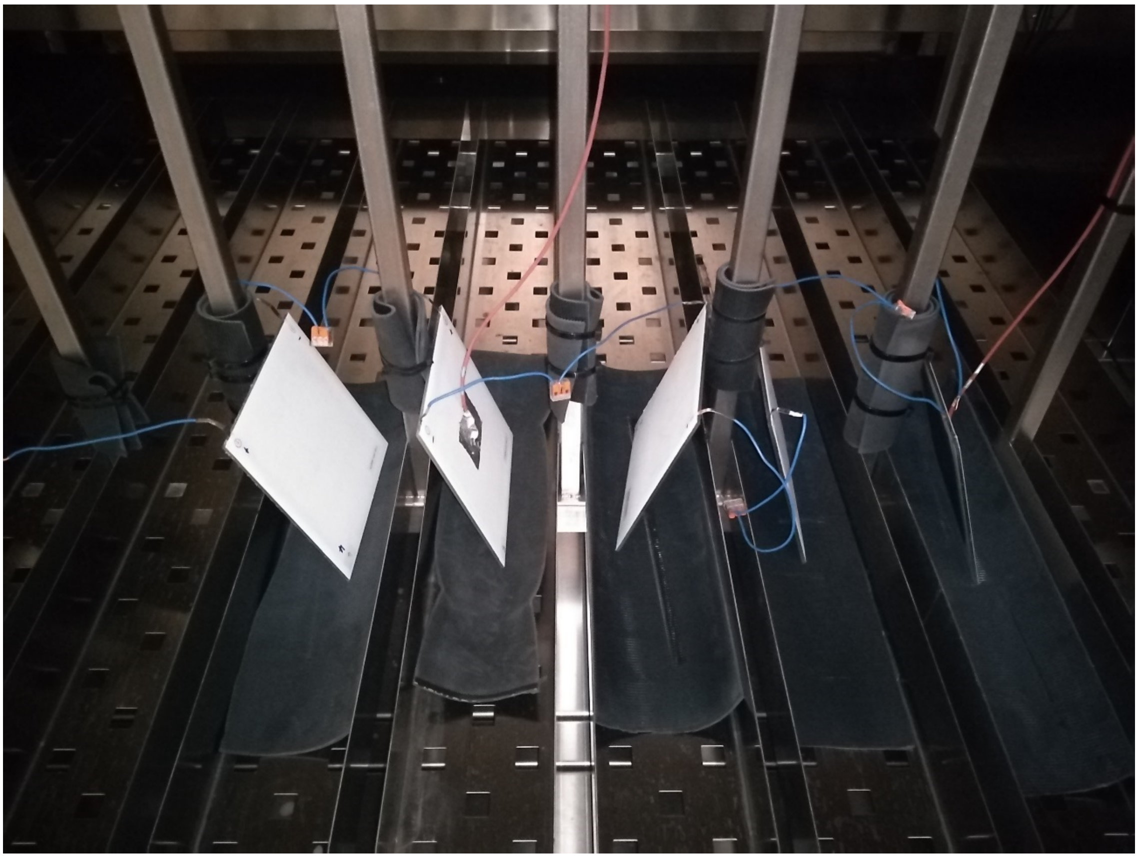


Fig. 20: The 5 samples inside the chamber at UCY.

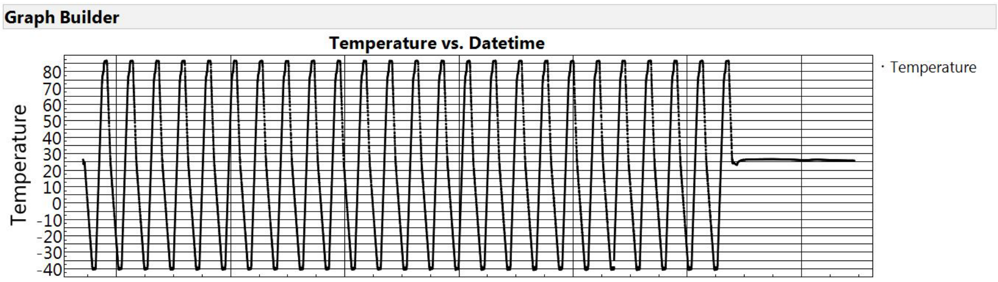


Fig. 21: Thermal cycling profiles

The 5 samples were thermally cycled from -40°C – 85°C 25 times and the chamber temperature was measured and shown in figure 21. Normally 200 cycles are recommended. Results of the parameters, Isc, Impp, Pmax, Vmpp and Voc are shown in percentages pre- vs post thermal cycling in figure 22.

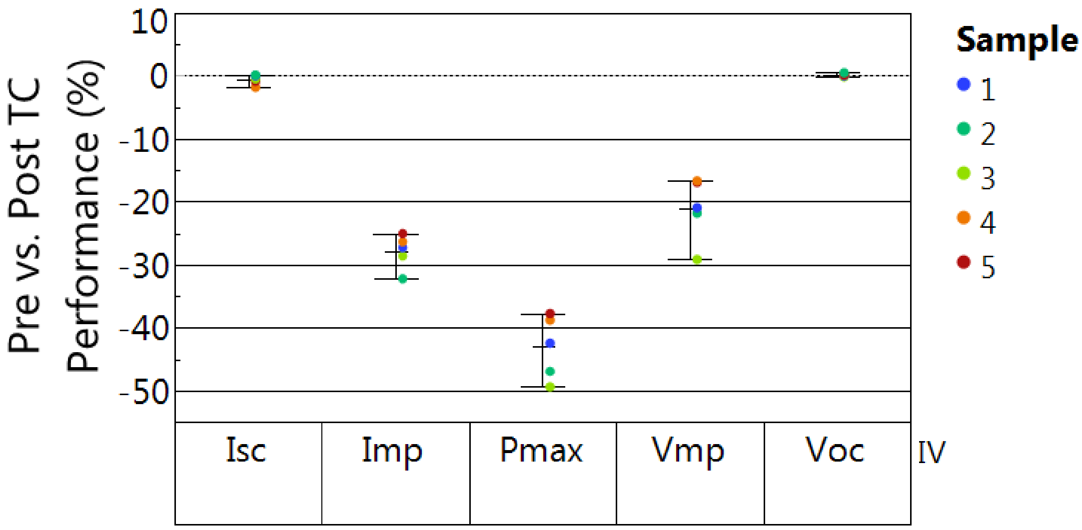


Fig. 22: Parameter degradation in percentage after 25 cycles of thermal cycling.

A loss in performance of 40-50% after 25 cycles of thermal cycling is critical for long term performance. In parallel with the test at UCY, DTU Fotonik have invested in a small chamber where thermal cycling can be done of minimodules up to 4 cells in size:

Fig. 23: Thermal cycling test bench at DTU Fotonik.

Since the tests take a lot of time it was not before the end of the project that the weaknesses over time was discovered. It is therefore highly needed to have the thermal cycling setup close to the fabrication at DTU Fotonik, to speed up the testing procedures. After EUDP project the reliability problems will be investigated and hopefully solved in a newly granted proof-of-concept project for commercialization of the machinery for selectively dying of strings for solar panel production.

The demonstrator

A demonstrator was made including the solar panels as a module in Kompromen slate facade systems. The solar panel is not perfect but blends rather seamlessly into the façade and have to be seen almost perpendicular to the wall to spot its solar cells.

Fig. 24. Solar panel with ADE treated solar cells at NinesPV and selectively dyed strings.

Commercialization

The project had 2 innovative tracks that was aimed for commercialization in combination. The black silicon treatment of the solar cells and the treatment of the highly reflective busbars of the solar panel making all the parts a black canvas perfectly tailored for building integration. The cheapest silicon solar cells are polycrystalline solar cells, which are blue, and therefore, the black silicon treatment will make them black, give them higher performance, and was therefore a way to get the same properties of the high-end mono crystalline solar cells which can be made black, and some even have no connectors on the front side and the panels can be made totally black. The 2 individual innovations are shown on figure 25 and 26 below.

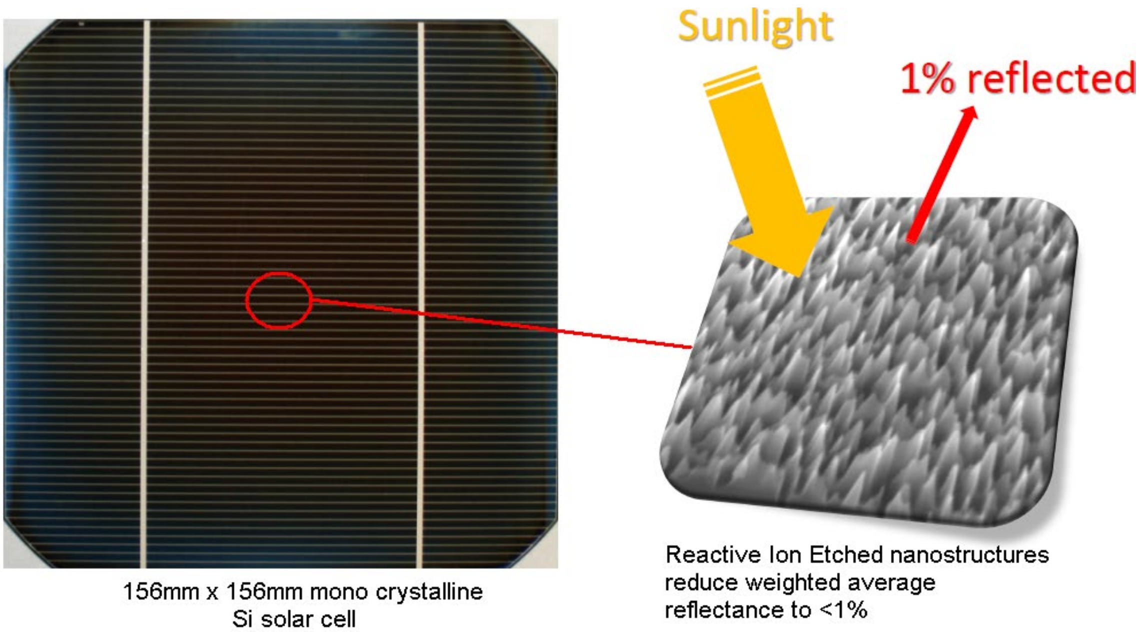


Fig. 25: Concept of nanostructures etched on commercial Si solar cells by mask-less RIE-texturing.

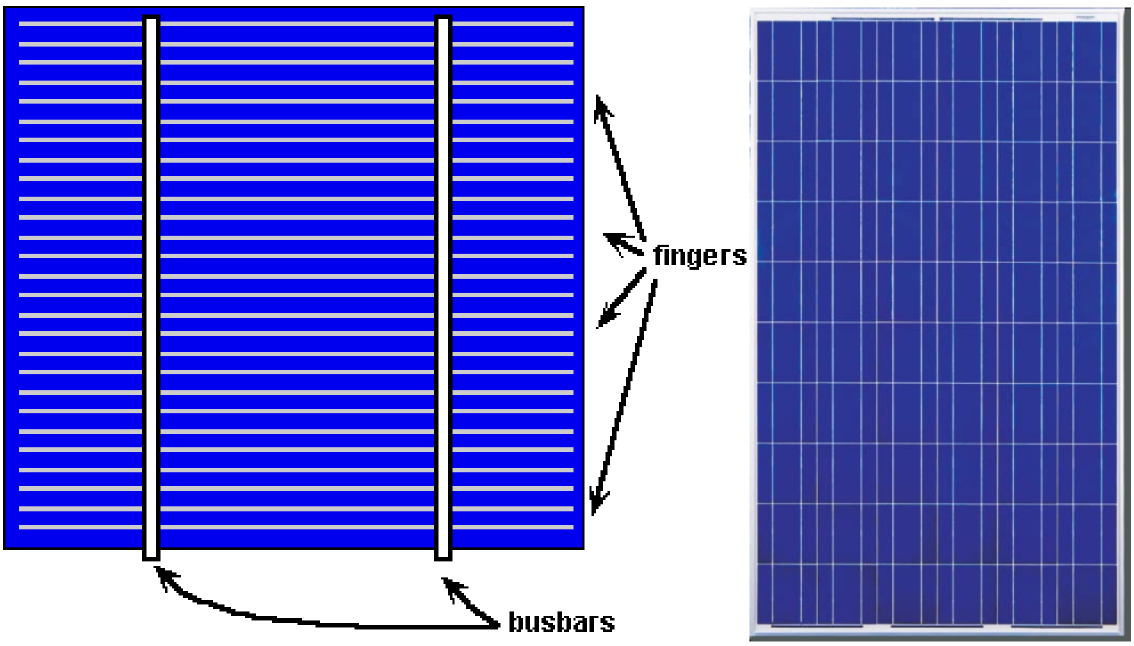


Fig. 26: Left: Silicon solar cell principle sketch showing the busbars and fingers; Right: Solar panel where the soldered-on busbars by solder tabs can be visually seen.

During the project the silicon industry have changed gradually from slurry-cutting to diamond saw cutting of silicon into wafers which gives a much higher yield and therefore more wafers from the same materials and lower cost of silicon. The silicon processed by diamond saw cutting cannot be post-processed by traditional etching to obtain low reflectivity which is important for high efficiency, but the processes worked on in this project, RIE and ADE works with the new manufacturing processes.

A patent has been filed "INTERNATIONAL PATENT APPLICATION NO. PCT/DK2019/050150 - A SOLAR PANEL COMPRISING LOW REFLECTANCE TABBING RIBBONS" (filing date May 14th, 2019). The patent claims using the combination of processes for making a black panel but also the machinery for the doing the selective dying by electrochemical processes are protected. This innovation in itself has received a Proof-of-Concept grant (0.5 mioDKK) from DTU to industrialize the machinery for selectively dying the strings.

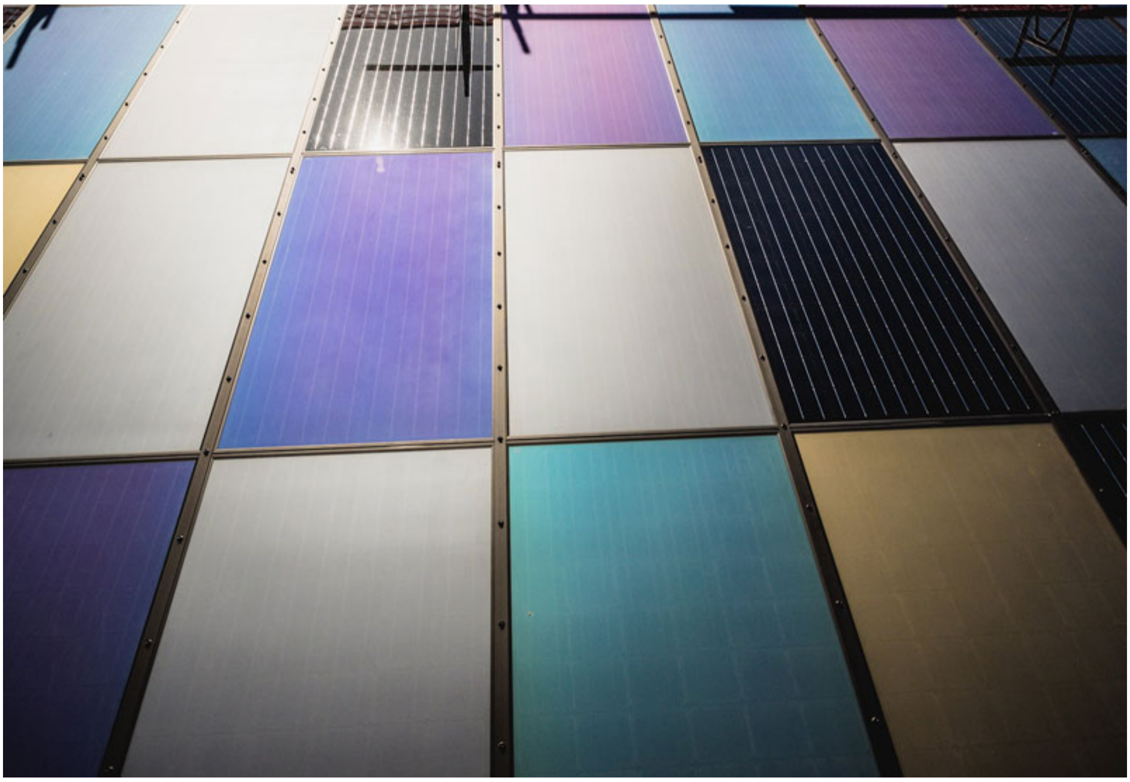


Fig. 27: Colored PV panels

The market for building integrated photovoltaics are twisting towards more and more colored solutions where the glass (or a foil) in front of the solar cells are dyed reflecting a color to the eye and transporting the rest of the solar rays to the solar cells for energy production. The black silicon with black strings therefore is a perfect cheap canvas for colored modules. If the strings are highly reflective, they can see through the colored front and distorts heavily the effect of the coloring of the PV panel. Therefore, time is in this sense working for the solution developed in this project. Another trend in the solar cell production optimization roadmap is the introduction of more and more busbars. The standard is now 5-6. Since more busbars means less width of the individual busbar so the reflection problems become less prevailing. Multiwire technology and back-contact solar cells has no visual contacts in front so the solution developed in this project might only have say 10 years of relevant market, and therefore especially the machinery, where several string producers have shown interest in integrating it in their production line to produce selective black dyed strings that never bleach as a niche product though servicing a rather massive niche. The problems with life time (shown in the thermal chamber test) though must be solved.

Since the project still is on TRL level 7 it has not yet shown increased turnover at the involved companies. It has though protected valuable technology, that is explored for a potential spin-off from DTU or as license sale to the string producers which is an obvious market for the machinery developed and protected in the project. This work will be continued in the proof-of-concept project following the calendar year 2019.

Dissemination

The exploratory work performed on advanced physical characterization and passivation of RIE textured black silicon at DTU Nanotech resulted in 3 peer-reviewed publication, 3 conference proceedings, and one conference oral contribution.

- B. Iandolo, A. P. Sánchez Nery, R. S. Davidsen, O. Hansen, *Phys. Status Solidi RRL*, 2018, 1800477, DOI: 10.1002/pssr.201800477 (on minimizing surface damage in black silicon)

- B. Iandolo, R. S. Davidsen, and O. Hansen, *Solar Energy and Solar Cell Materials*, 2018, 187, 23-29, DOI: 10.1016/j.solmat.2018.07.014 (on avoiding blistering of Al_2O_3 when used as surface passivation)

- B. Iandolo, I. Mizushima, R. S. Davidsen, Peter T. Tang, and O. Hansen, *Jpn. J. Appl. Phys.*, 2018, 57 08RH01, DOI: 10.7567/JJAP.57.08RH01 (on combining black silicon with black tabbing wires)

- A. R. Stilling-Andersen, O. Solodovnikova, R. S. Davidsen, O. Hansen and B. Iandolo, "Diffusion of phosphorous in black silicon" Proceedings of WCPEC7, Waikoloa (USA)

- B. Iandolo, R. S. Davidsen and O. Hansen, "Single and double side textured black silicon require different annealing conditions for optimal passivation with ALD Al_2O_3" Proceedings of WCPEC7, Waikoloa (USA)

- B. Iandolo, M. Plakhotnyuk, M. Gaudig, R. S. Davidsen, D. Lausch, and O Hansen "Dry Etch Black Silicon with Low Surface Damage: Effect of Low Capacitively Coupled Plasma Power" Proceedings of 2017 EUPVSEC, Amsterdam

Furthermore, DTU Fotonik has led the following publications:

- Riedel et al., 2018 *Interlaboratory Comparison of Methodologies for Measuring the Angle of Incidence Dependence of Solar Cells* 35th EU PVSEC, Brussels, Belgium.

Riedel, N, Santamaria Lancia, AA, Amdemeskel, MW, Plag, F, Kröger, I, Slooff, LH, Jansen, MJ, Carr, AJ, Manshanden, P, Bliss, M, Betts, T, Jauregui, IP, Mayo, ME, Balenzategui, JL, Roldan, R, Kräling, U, Baarah, G, Zirzow, D, Lee, K, King, B, Stein, J, Kedir, C, Watts, J, Sauer, K, Thorsteinsson, S, Poulsen, PB & Benatto, GADR, Incident Angle Modifier Round Robin Updates, 2019, 22-23Oct., 12th PV Performance Modeling and Monitoring Workshop - Albuquerque, United States.

The machine has been shown at IPUs stand at DTU's High Tech Summit 2019, 30-31 October.

1.6 Utilization of project results

As described above the project has led to a patent protecting the machinery for selective dying the strings and use with (and without) the black silicon treatment of the solar cells. The patent is owned 50% by DTU and 50% by IPU, and a proof-of-concept (PoC) investment of 500kkr. has been attracted to investigate the commercialization of the machine after the end of the EUDP project addressed in this report.

Since the project ends at TRL level 7, the involved companies cannot implement the technologies before higher TRL levels are reached and the investment above will deal with especially the stringing machinery, that is the major innovation in this project that potentially can lead to

- A new company producing the machines
- A company transferring knowledge to machine producers for the PV industry addressing especially the string producers
- License sale

The PoC project investigate these routes further.

The research has benefitted heavily the new Study Line within Solar Energy that DTU Fotonik has been leading the creation of while this project has been ongoing. It was announced in 2017 and launched in September 2018 with great success. The study line consists of many new photovoltaics courses and one dedicated to building integrated photovoltaics. This EUDP project has been used as a corner stone for teaching students in new innovative ways of addressing the needs from architects and other stakeholders concerned with aesthetics of the building envelope. New technologies are needed to meet the demands and there is a great opportunity now to create new products serving this market while supporting the transformation towards a sustainable energy production.

The large interest from Danish industry in building integrated photovoltaics has further led DTU to investment in a R&D facility at DTU Fotonik at Risø Campus in Roskilde where new concepts of BIPV solutions can be fabricated and tested. This facility also serves as hands-on teaching of DTU students and industry on fabrication of BIPV solutions.

Fig. 28: Photo from a class in applied photovoltaics where the students build their own PV module.

1.7 Project conclusion and perspective

The project has successfully addressed its objectives and the major deliveries can be concluded below:

- Development of black electroplating methods to make the front metal busbars black
- Development of a machine to automatically process the strings to selectively dyed
- Design and production of Black Silicon cells with black busbars
- Manufacturing of a demonstrator module fitting in Komproment's product catalogue
- Reliability test of black silicon treated cells and the chemically processed busbars in the panel

The black silicon BIPV serves as a perfect low-cost canvas for the all the new colored technologies being introduced to the market these days. Here a black canvas is needed for best product performance and visual impression. The project has therefore led to important technology that has high value both to the research community and for commercialization through different routes.