Final report

1.1 Project details

Project title	High-efficiency nano-structured solar cells
Project identification (program abbrev. and file)	ForskEL-project 2015-1-12274
Name of the programme which has funded the project	ForskEL
Project managing company/institution (name and address)	Martin Aagesen Gasp Solar ApS, Hovmarken 23, 2640 Hedehusene
Project partners	Gasp Solar ApS, DTU CEN, DTU Fotonik
CVR (central business register)	Gasp Solar: 35 22 77 25, DTU: 30 06 09 46
Date for submission	August 12, 2016

1.2 Short description of project objective and results

The project objective was to develop an optimized solar cell structure from Gallium Arsenide Phosphide nanowires grown on silicon solar cells. The goal was a two junction solar cell consisting of a top nanowire solar cell standing on a bottom silicon solar cell and having a combined efficiency of 20%.
In parallel, an objective was also to form a scientific research community, capable of backing further research into improving the cell efficiency.

The project formed the scientific community and achieved a record conversion efficiency, for a nanowire based solar cell on a silicon substrate, of 5%. The project did however not succeed in transferring the nanowires to a silicon solar cell during the time frame of the project, so an expected additional ~10% efficiency boost was not realized.

--------------------DK version---------------

Projektets mål var at udvikle en optimeret solcellestruktur basseret på gallium-arsen-fosfor nanowires dyrket på en silicium solcelle. Målet var en dobbelt-junktion solcelle bestående af en øvre nanowire solcelle dyrket på en nedre siliciumsolcelle og havende en samlet effektivitet på 20%.
Et ekstra mål for projektet var at skabe et akademisk forskningsfællesskab som ville være i stand til at støtte op om den videre udvikling af solcellen efter projektet var slut.

Projektet skabte forskningsmiljøet og lykkedes med at opnå en, for den type nanowire solcelle på silicium, rekord effektivitet på 5%. Det lykkedes derimod ikke, indenfor projektet tidsramme, at dyrke nanowirerne på siliciumsolceller, således at en yderligere ~10% effektivitetsforøgelse kunne blive realiseret.

1.3 Executive summary

The project goal was a 20% efficient nanowire based tandem solar cell, aimed at demonstrating the commercial perspectives of the design to future customers and investors. The project also had a business development part focused at increasing the likelihood of Gasp Solar attracting new funding such that a higher efficiency solar cell (35%) could be produced and marketed. This subsequent development phase should be carried out under a corporate development partnership agreement.

For the technical part of the project two subcomponents had to be developed, 1) a new imprint stamp with an optimized pattern for growing positioned nanowire structures on a silicon surface, and 2) a high efficiency silicon solar cell made on the non-standard Si(111) crystal orientation. The imprint stamp was to be used for making the patterns for positioning the nanowire growths on both the non-solar silicon substrates and on the solar cell substrates. Afterwards a series of iterative nanowire growths and characterization steps was to be carried out and this should result in the wanted high efficiency tandem solar cell.

From the start, delays were encountered due to mainly technical problems with the imprint equipment and with the processes used for making the imprint stamp. Also, problems with finding manufacturers that could produce the high efficiency silicon solar cells created delays. In the end both problems were solved, although the patterning of the silicon substrates had to be done by means of the more expensive electron lithography method. The iterative growth and characterization process was carried out, and each time gave new and important data about the solar cell structures. We were able to go from the initial ~1% nanowire solar cell efficiency, to first ~3% and finally to 5% efficiency. The initial delays unfortunately meant that the project were not able to also optimize the growth parameters for growing on the new (111) oriented silicon solar cell substrates. During the project there was only time to carry out two growth attempts, both of which did not produce any nanowires. Post project work will continue on this matter.

The results from the technical part of the project shows that making a nanowire solar cell requires a highly detailed understanding of the epitaxial growth process. The results also show that it is possible to achieve a high efficiency solar cell as demonstrated by the achieved 5% efficiency. The project was due to the time constraints not able to combine the nanowire solar cell with the silicon solar cell substrate, such that an additional 10% efficiency could be added.

On the commercial part of the project the conclusion was that a 20% efficient solar cell initially would be enough to gain the interest of some of the major vertically integrated solar cell manufacturers. The work carried out in the project however also showed that when identifying the most suitable collaboration partners focus should also be put on equipment manufacturers, such as Meyer Burger and Applied Materials, since they, opposite to the solar cell manufacturers, are more likely to have the financial liquidity to support our development.

The project results will continue to be improved post project. The current research setup can continue developing the high efficiency nanowire solar cells, as well as work on growing them on the silicon solar cell substrates obtained in the project. This will eventually result in a combined efficiency of 20%. Using the knowledge obtained in the dialogs with persons from the solar cell industry, it will then be possible to identify and approach new potential collaboration partners.

1.4 Project objectives

To achieve the project goal a list of sub-objectives was planned to be carried out. Each of the sub-objectives had one or more milestone attached to keep track of the progress made and whether the project was delayed. The list of technical sub-objectives/tasks planned at the start of the project was:

1. Design and fabricate a new imprint stamp needed to obtain an improved nanowire growth pattern.
2. Acquire high efficiency silicon solar cells fabricated in Si(111) substrates using standard commercial methods.
3. Imprint the new pattern on both p-type silicon substrates, and also on the new silicon solar cells as they become available later in the project.
4. Grow nanowire solar cells on the imprinted substrates by means of MBE.
5. Characterize the grown structures using TEM techniques including Off-Axis Electron Holography and Energy Dispersive X-ray Spectrometry (EDX).

6. Fabricate a complete demonstrator solar cell with an improved efficiency.
7. Investigate nanowire-photon coupling effects that can assist raising the peak possible efficiency of the Gasp tandem solar cell to above the current 35%.

The milestones associated were:

Technical:

1. M1: First holography potential mapping of GaAsP NW solar cell
2. M2: First imprinted p-type silicon substrates
3. M3: First diced/cut silicon substrate with NWs on
4. M4: 10 4" silicon (111) solar cell substrates delivered and tested
5. M5: First core-shell nanowire growth on standard Si(111) solar cell
6. M6: Electron holography image showing a potential drop between n- and p-region of 1.4eV

Commercial:

1. CM1: Meetings with key players within IoT and Energy harvesting
2. CM2: Have identified key persons within target markets and R&D
3. CM3: Strengthened board of directors and advisory board
4. CM4: Investor pitch and R&D plan ready for reaching 35% efficiency
5. CM5: Shortlist with CEO candidates for Gasp Solar

From the start it was expected that the main risks in carrying out the project was on the availability of the most critical piece of equipment, the MBE system, which is required for growing the nanowires. In order to alleviate the MBE risk contact was established to a back-up MBE facility.
During the execution of the project it soon became clear that although some of the sub-objectives earlier had been carried out in almost identical ways, by either industry or project partners, it was not trivial to transfer them to the project. Also, since the project was heavily depending on the novel characterization method, Off-Axis Electron Holography, the staff specialized in this was critical. This was learned when the key holography characterization person received, and accepted, a job offer at Rice University in the US.

During project execution the four most critical delays turned out to be (in order of importance):

1. Imprint Stamp fabrication and patterning. Due to break down of equipment, non-optimized processing procedures, and a subsequent need for transitioning to Electron Lithography.
2. Si(111) solar cell procurement. Due to the non-compatibility between the thin semi-square solar cell substrates used in the PV industry, and the requirement for using thicker, (111) oriented, round SEMI-standard substrates for the silicon solar cell in the project.
3. Delays caused by staff changes, and the training of new staff for the holography characterization method.
4. Delays caused by temporary non-availability of the MBE system.

None of the four delays was in themselves critical for the project. Together they however meant that the short project, only 18 months, was not able to reach its final objective of making a combined tandem solar cell by growing a nanowire solar cell on the silicon solar cell substrate. The technical milestones in the project was not all met, and those that were met was not all met on time. Milestone M2 and M4 was delayed due to the imprint stamp and Si(111) solar cell difficulties, and milestone M5 and M6 was newer reached primarily due to delays with the imprint stamp, as well as the combined effect of all four delay reasons.

Although the delays were critical for the project result, it is important to mention that the overall execution plan for the project was sound and worked. During the project all of the sub-parts required to reach the final tandem cell was made available, and the efficiency of the nanowire solar cell was increased by a factor of five. In hindsight, what turned out to be the main critical part to reach the project goal was time. Instead of lasting 18 months the project should have run for 36 months.

The commercial side of the project was also affected by the technical delays. Contacting and talking with key players within IoT and Energy Harvesting (milestone CM1) was unaffected by the delays. However, identifying the most relevant and required skills for the board of directors and the advisory board proved difficult due to the low efficiency achieved at the time. The low efficiency obtained also made it non-relevant to start changing the CEO in

Gasp Solar, since focus had to remain on technical development. An investor pitch and R&D plan was made (milestone CM4). Without the ~20% efficiency of a demonstrator solar cell its ability to raise funding is however limited.

1.5 Project results and dissemination of results

The three main technical activities in the project was

1) Nanowire solar cell growth
2) Characterization of the grown nanowires using off-axis electron holography
3) Device fabrication and characterization

Concerning nanowire solar cell growth, focus has here been on optimizing the doping densities, growth of a shell around the core nanowire, and on optimizing the surface passivation layer. The result was an improvement in the crystal quality of the grown nanowires (figure 1), something that is important in order to increase the efficiency of the solar cell.

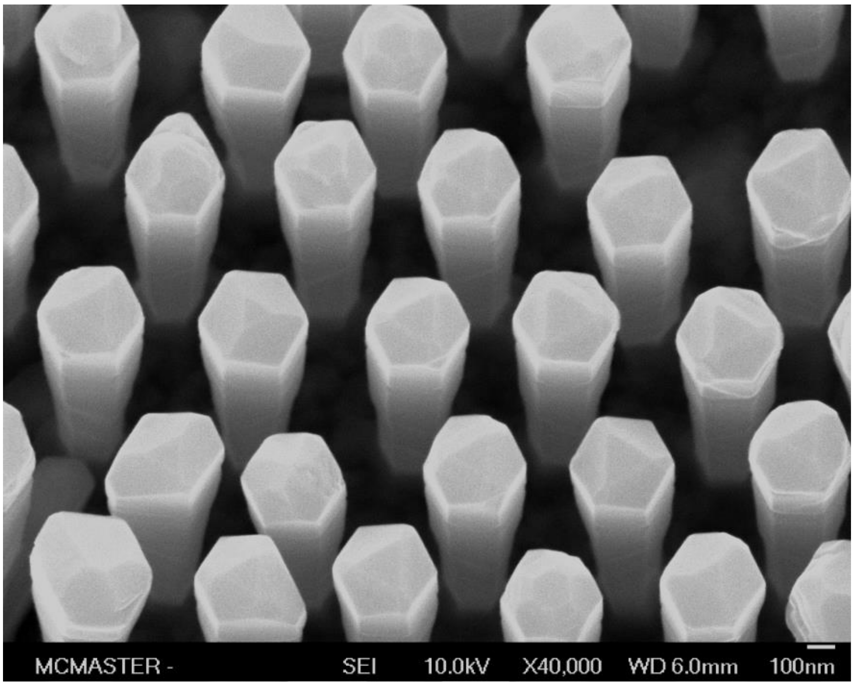

Figure 1, An array of core-shell nanowire solar cells grown on a silicon substrate.

In combination with off-axis electron holography it was possible to identify the main reason for the initial low solar cell efficiency to being insufficient doping in the core and shell. In figure 2 is shown a holography result showing that the build-in potential in the nanowire is very small, something that can be directly related to insufficient doping.

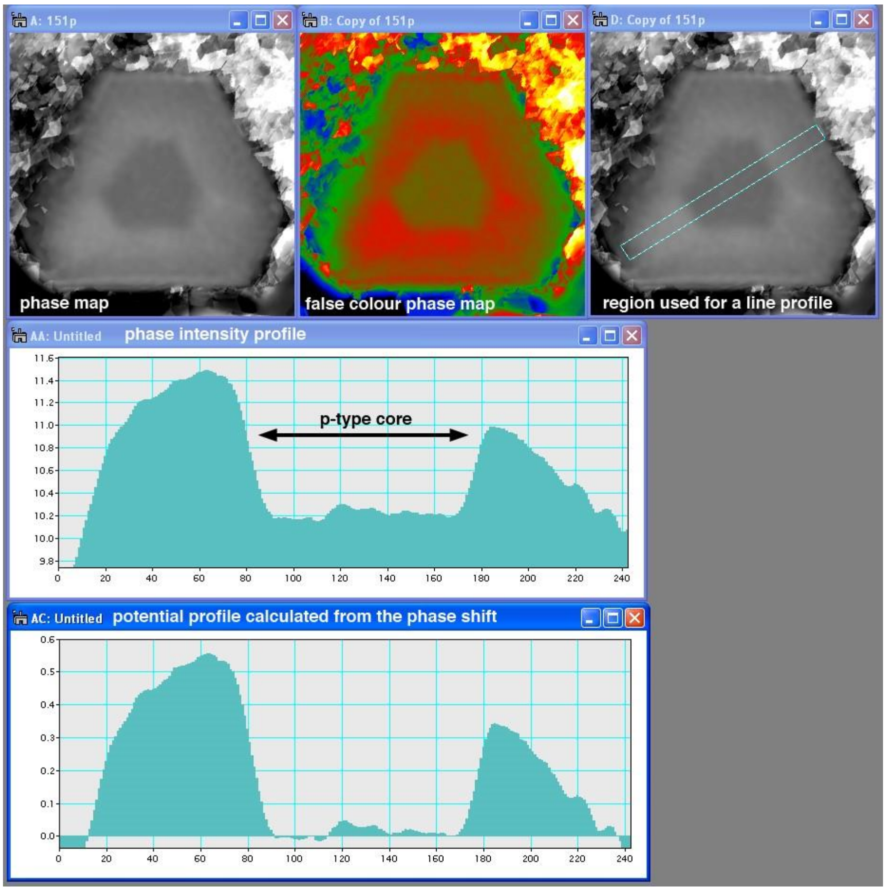

Figure 2, Off-axis electron holography mapping of a core-shell (p-n) nanowire solar cell. The bright (red) areas in the upper images are n-type and the dark center area is p-type. In the bottom plot, the build-in potential can be seen to be between 0.35 and 0.55 eV.

By doing several iterations of nanowire growth, device fabrication and TEM holography characterization, it was possible to increase the nanowire solar cell efficiency to 5% (figure 3). Although a factor of five in improvement relative to the efficiency at the beginning of the project, the holography characterization however still showed that the nanowires were at least partly depleted. Improvements in efficiency can therefore still be obtained "simply" by increasing the doping density.

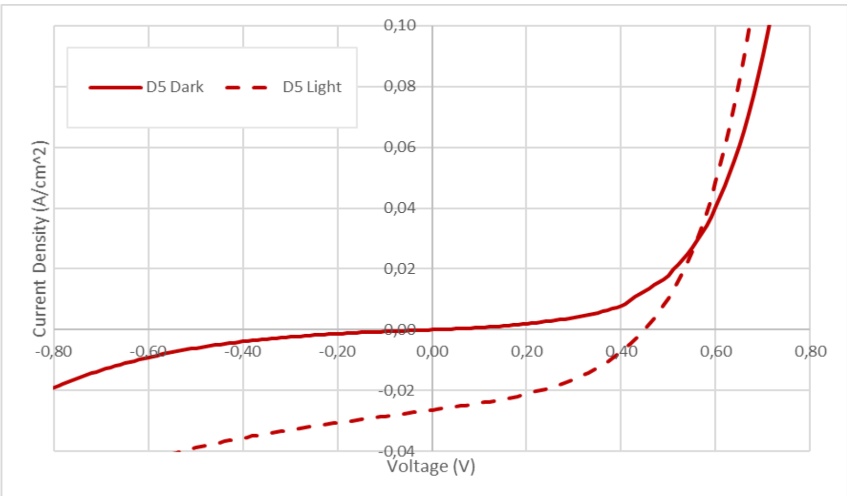

Figure 3, The IV characterization data for growth MBE1813 having a 5% peak efficiency. V_{oc}:0.45 V J_{sc}:26 mA/cm^2

At the end of the project the TEM holography characterization also gave us new important knowledge about doping incorporation during the nanowire growth, data that it would not have been possible to obtain in any other way. The results show that a reason for the insufficient doping of the core nanowire can be that the Be doping atoms are incorporated at preferential facets during growth and therefore become unevenly distributed (figure 4).

Phase map

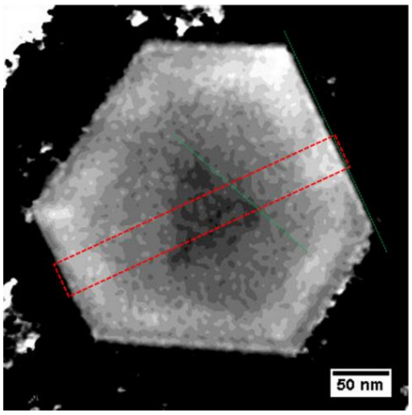

Figure 4, Off-axis electron holography image. Dark area is p-type and bright is n-type. It can clearly be seen that although the core nanowire is hexagonal in shape the potential caused by the p-doping forms a triangle. It is therefore not all of the core nanowire that is made fully p-type.

The commercial activities in the project was focused on positioning the company best possible in order to be able to raise the funding required for continuing development towards a 35% efficiency solar cell. The business development work was carried out mainly in the form of meetings and conversations with companies and persons identified as having knowledge valuable to Gasp Solar. The outcome of the meetings has been an improved knowledge about the markets and the different commercial and technical mechanism guiding them. As a result, it has been decided to also focus on the major equipment manufacturers since the margins for the non-vertically integrated solar cell manufacturers are so small that most of them are not able to spend capital on own R&D projects. Likely collaboration partners for doing co-development of the final solar cell, has therefore been expanded to also include equipment manufacturers.

The different markets for the nanowire solar cell has also been investigated. The conclusion has been that although the market concerned with powering stand-alone Internet-of-Things devices is interesting, then it is tiny in size compared to that of roof-top solar. Although the 35% efficient nanowire solar cell will be more expensive to fabricate than current silicon cells, the increased efficiency of the solar cell will, at system level, mean that the cell still can be very competitive in the roof-top solar market. During the business development work it was also confirmed that several large solar cell companies, like the French company Total, is searching for ways to increase the efficiency of their solar cells (the SunPower cells) to above the ~26% efficiency limit that all silicon cells are encountering. The results obtained in the projects commercial activities support that there is a large market in roof-top solar for the nanowire solar cell, and they support that it will be possible to find a co-development partner once ~20% efficiency has been demonstrated.

The technical and commercial objectives of the project have not been reached do to the delays encountered in the technical part of the project. The results obtained in the project however all confirm that the nanowire solar cell is both technically possible to develop as well as commercially interesting.
Since Gasp Solar is still in an R&D and fundraising stage, it has not yet resulted in an increased turnover, export or employment. Thanks to the project Gasp Solar is however today closer at raising funding for continuing the development, than prior to the project. With continued R&D, based on the project results, Gasp Solar expects that the project in the future can result in an increased turnover and employment.

So far the results of the project have been disseminated at a conference and in a scientific journal. Work is ongoing for publishing the latest holography results on doping incorporation during nanowire growth.

1.6 Utilization of project results

The three participants in the project each had their own reason for participating. The two academic project partners, DTU CEN and DTU Fotonik participated because the project matched and added to their ongoing research interests. DTU Fotonik had the expertize for making nanometer size holes in a thin layer of SiO_2, and was interested in measuring how photons interact with an array of nanometer sized vertical nanorods grown in such holes. They are, and will continue to, use the structures grown in the project for experimental research, that not otherwise would have been possible for them.
DTU CEN participated in the project because they are pioneering the characterization method of off-axis electron holography and for that they need to have access to purpose made nanostructures where the doping concentrations has been changed systematically. DTU CEN will be using the results for improving the theoretical models on which their experimental work is depending. For both DTU Fotonik and DTU CEN, as well as for Gasp Solar, the collaboration and its accompanying scientific discussions allowed for expanding and understanding each of our research areas significantly.

Gasp Solar is the only participant that from the start had a commercial focus with the project. Although the majority of the work has been on developing the nanowire tandem demonstrator solar cell, it has always been with the purpose of using if for raising funding, such that development can be continued towards the final 35% efficiency solar cell. Although the results obtained in the project has not met those hoped for at the beginning, the results are still good enough to be able to demonstrate that there is reason for continuing with nanowire solar cell R&D.

In Gasp Solar the results are now part of the R&D results outlining the current development plan towards a 35% cell. The development plan is part of the pitch being given to potential investors and which, in time, hopefully will ensure that additional funding can be raised. The combined commercial and technical results obtained in the project has helped focus the Gasp Solar business plan such that it now is purely on roof-top solar. The billion-dollar market available for a high-efficient solar cell, on roof-tops where a limited area is available, is substantially better than the alternative niche markets like energy harvesting for Internet-of-Things. The competition in the market is mainly from existing vertically integrated solar cell developers looking for a way to pass the ~26% practical efficiency limit of the current silicon based solar cells. The only competitor using nanowires for improving the efficiency of silicon solar cells are the Swedish company Sol Voltaics, which in May this year closed a $12.5 million equity funding round. Gasp Solar therefore remains optimistic that it will be possible to raise funding for further solar cell development.

During project execution there has not been obtained new results, or achieved new insight, that has been patentable. There are therefore no plans to take out a patent.

The results obtained in the project does not, as of now, contribute to realizing the energy policy objectives. It is however the expectation of the project participants that the results are good enough to help ensure that further research and development will be carried out; R&D that then will have a good change for contributing to realizing the energy policy objectives.

1.7 Project conclusion and perspective

The conclusions made from the project can be summarized as follows:
Technical conclusions:

1. Making a high efficiency nanowire solar cell is possible.
2. Be-doping, and nanowire doping in general, is not trivial and needs to be carefully controlled.
3. The characterization method, Off-Axis Electron Holography, is an absolutely invaluable tool for characterizing doping densities in core-shell nanowires.

Commercial conclusions:

1. The nanowire tandem solar cell will have a good combination of material price and efficiency, when measured at system level.
2. Much of the technical advancements made in the commercial solar cell market is implemented by the PV equipment manufacturers. The reason is that the margin for solar cell manufacturing is small.

The conclusions obtained from the project support that continuing R&D on the nanowire tandem solar cell makes sense. The R&D work should focus on the lowest hanging fruits to achieve a ~20% efficiency as quickly as possible, such that a development partnership can be formed with a major PV company. The lowest hanging fruits appears to be increasing the doping density in the nanowires, such that their full build-in potential (open circuit voltage) can be realized. The conclusion from the project is that the best tool for determining doping concentration, and evaluate the new nanowire growths, is off-axis electron holography.

The conclusion from the project is also that the development path forward ought to include an attempt to determine more precisely how the final tandem solar cell production system should be designed. Based on that, contact should be made to suitable equipment manufacturers to test if there are possibilities for co-developing the solar cell with them.

Annex

Dissemination:

- EMN Meeting on Nanowires, Amsterdam: http://emnmeeting.org/nanowires/
- IEEE Photovoltaics paper, Characterization of a Ga-Assisted GaAs Nanowire Array Solar Cell on Si Substrate, DOI:10.1109/JPHOTOV.2016.2537547