Eindrapportage

Advanced Nanolayers and Passivating Contacts

General

Project number	TEZ114008
Project title	Advanced NanoLayers and Passivated Contacts
Project Coordinator Project Partners	ASM Europe BV Delft University of Technology Eindhoven University of Technology Energy research Centre of the Netherlands ECN
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Summary

Within this project ASM together with TU/e, TUD and ECN developed novel processes for so-called passivating and carrier selective contacts, also called passivating contacts. The surface passivating quality of passivating contacts based on poly-silicon researched in this project is excellent and implied V_{OC} values above 730 mV have been obtained. Integrating this type of contacts in completed solar cells resulted in open area efficiencies above 20% for cells with contacts on both sides and above 22% efficiency for back-contacted (IBC) cells, the best silicon cells made in the Netherlands (at that moment). Large area industrial processes resulting in excellent surface passivation was developed as well. On completed large area cells good V_{OC} values were reached, close to 700 mV and showing minor degradation during cell processing.

More fundamental studies on passivating contacts and novel passivating layers based on metal oxides were carried out as well. Studies on surface passivation by atomic layer deposited Al_2O_3 layers were studied extensively and resulted in a book chapter. First promising results on surface passivation by TiO_2 layers were demonstrated, and will be further explored in other projects.

Introduction

Performance of mainstream industrial solar cells based on p-type Si wafers and a full-area metal contact is chiefly limited by recombination processes. To further increase solar cell efficiency, new cell concepts are required which feature surface passivation films on front and rear side. Increasingly, these cell concepts will be based on n-type Si wafers as these have higher stabilized bulk lifetimes than p-type Cz wafers. These n-type cells demand surface passivation films which are simultaneously suitable for both n^+ and p^+ doped areas and can be applied at low cost. A subsequent step in the solar cell evolution is to address the recombination under the metal contacts. This requires a novel contact stack which includes an ultrathin precisely engineered tunnel and passivation film. The latter is a good example of a “functional film” that needs to meet a variety of requirements.

In the recent years the Fraunhofer Institute for Solar Energy introduced the integration of so-called passivating and carrier selective contacts (in short passivating contact) in n-type solar cell processing. The front side of this cell still consists of a diffused boron based emitter, but for the rear side a passivating contact is applied. The structure contains a ultrathin tunnel silicon oxide and a highly doped poly silicon layer. Metal oxides combined with a thin tunnel layer can be used as passivating contact as well. Both novel layer structures were researched within this project.

Objectives and scope

The objective of the project is developing a high-efficiency and cost-effective solution for advanced passivating contacts and post anneals for implanted poly-Si junctions that can be industrialized for application in large-volume vertical furnace toolsets. The solutions have a focus on process technology development. The PV industry is currently using horizontal furnace equipment, except for Atomic Layer Deposition (ALD) passivation, even though the larger vertical furnace equipment offers cost and performance advantages. The large volume enables larger batches to be processed (typically 2x higher) on a very small footprint. Vertical processing has inherent technical advantages: no gradient of the cell due to the positioning, fast ramp and fast cool down capabilities, low O_2 and water ambient upon inserting/removing the boat, precise injection of precursor, boat rotation during processing and hardware features extending uptime and PM intervals. The competitive processes developed should be transferable to industry (PV manufacturers) and help to increase the sales of Dutch process equipment.

Within this project, the following technologies were investigated and assessed with respect to future industrialization:

Processes for doped poly-Si layers. Ion implantation is seen as one of the future industrial technologies to dope poly-Si layers. After doping poly-Si layers by ion implantation, annealing is required. High temperature annealing with ultra-high ramp and cool rates have been shown to provide benefits. The influence of the annealing recipe and the benefits on cell level need to be evaluated. The aim of the project was to develop junctions based on poly-Si layers and ion implantation resulting in low recombination.

Passivating surfaces. Understanding and development of (novel) ALD films and stacks in combination with pretreatment and thermal post treatment.

Solar cells with passivating contacts. Design and testing of passivating contact schemes for further improvement of the cell efficiency. Understand the possible trade-offs in engineering these contacts and provide solutions for industrial process flow. Vertical furnace processes such as poly Si and thermal oxide can be included.

Towards ultrathin solar cells. The processes described above will be assessed for potential application to future ultrathin solar cells. The individual processes will be evaluated for silicon foil material (<50 micron).

Approach

In this project, novel schemes for the passivation of highly doped surfaces and contacts were investigated. We used ion implantation for surface doping poly-Si layers and focused on the activation anneal and subsequent passivation. The project consists of four workpackages and each work package focusses on a different process/application that can potentially be developed and/or transferred to the ASM vertical batch furnace.

In WP1, the focus was on doping profile optimization of ion-implanted in poly-Si layers by high-temperature post-annealing and oxidation processes compatible with the ASM vertical batch platform. The doping profile and surface concentration play an important role in the design of the surface passivation scheme and the minimum surface recombination velocities that can be achieved. Trade-offs exist between high open-circuit voltage, lateral conductivity, metal contactibility, and proper implant damage removal. Control over doping profiles is therefore essential to maximize the effect of surface passivation and cell performance.

For WP2, the focus was on Atomic Layer Deposition (ALD) processes compatible with the ASM batch platform. The research focused on SiO_2/Al_2O_3 and other novel surface passivation schemes. Another focus was on diffused n^+ and p^+ surfaces (see WP1) and optimizing the passivation performance by adjusting process conditions and/or pre-treatment. The goal was to reach optimized and tailored passivation and pre-clean solutions which can readily be applied in industrial solar cells.

In WP3, the work was taken one step further by developing passivating contacts. The focus was on oxidation and Low Pressure Chemical Vapor Deposition (LPCVD) Si-based processes compatible with the ASM batch platform. The work will include the design, simulation and understanding of the relevant properties of passivated contacts. On the basis of these studies, various concepts were developed and tested on completed solar cells.

In WP4, the above described innovations were evaluated for very thin substrates "Si foils" to assess feasibility and benefit on these future wafers. Unfortunately, Si foil material is not available anymore and the feasibility was carried out based on experimental findings on thicker material.

Results

Junctions of and passivation by poly-Si based structures for high-efficiency solar cells

To reduce recombination losses it is important to understand mechanisms related to surface passivation and the effect on recombination. Both experimental and modelling studies were carried out at TU/e and it was found that:

- Auger recombination, which is the principal recombination pathway in the emitter, can be significantly reduced in two ways, while remaining the same sheet resistance by forming
  1. very deep, lightly-doped (N_d~10^{18} cm^{-3}) diffused emitters
  2. very abrupt, degenerately doped emitters (N_d>10^{20} cm^{-3}) (for instance a doped poly-Si emitter)
     - Doping confinement in thin poly-Si layers (on top of tunnelling SiO_2 coating c-Si bulk) allow for very low J_0
- Increasing the surface doping concentration can be beneficial to reduce surface recombination without inducing additional Auger recombination.
- Various publications on recombination mechanisms in doped regions cover the results in detail.

See list of publications for more information.

At PVMD group (TUDelft), the passivation properties of carrier-selective and passivating contacts based on tunneling SiO_2 and ion-implanted poly-Si were extensively studied within this task. The poly-Si layers were applied using Low Pressure Chemical Vapor Deposition (LPCVD), a process compatible with the vertical ASM system. So-called symmetric samples endowed with both n-type and p-type poly-Si layers were realized, enabling, via quasi-steady-state photo conductance (QSSPC) technique, the study of minority carriers lifetime as function of injection level. A symmetric sample was formed by n-type FZ c-Si wafer double-side coated with first a wet-chemically grown ultra-thin (~1.5 nm) tunneling SiO_2 and then with low-pressure chemical vapor deposited intrinsic a-Si. Both sides were afterwards ion-implanted with either phosphorous or boron atoms. Then, such coated wafer was annealed at high temperature (T_{ann} > 850 °C) for dopants' activation and crystallization. Finally, an *hydrogenation* step consisting of another annealing (T_{ann} ~ 450 °C) in N_2/H_2 environment was executed for boosting layers' performance. Next to QSSPC, also other characterization techniques were deployed, such as Transmission Electron Microscopy (TEM) for thickness verification of tunneling SiO_2; Raman spectroscopy for crystallinity fraction in post-deposition implanted/annealed poly-Si layers; Electrochemical Capacitance-Voltage (ECV) at ECN for active doping concentration profile. The experiments investigated the effect on passivation of poly-Si thickness, implantation dose, implantation energy, annealing temperature. In the table below, the best n-type and p-type doped poly-Si layers are reported, featuring high implied open-circuit voltage (i-V_{OC}) after the *hydrogenation* step.

Table 1: Effective lifetime at injection level $\Delta n=10^{15}$ cm^{-3}, sheet resistance R_{sh} of the doped poly-Si, recombination current J_0 and implied V_{OC} for structures with differently doped poly-Si layers.

Doping type	**τ_{eff} (10^{15} cm^{-3})** [ms]	**R_{sh}** [Ω/□]	**J_0** [fA/cm^2]	**i-V_{OC}** [mV]
n-type	**18**	**85**	**4.5**	**735**
p-type	**4.5**	**150**	**11**	**716**

Such high-performance carrier-selective passivating layers, which constituted the doped regions in the solar cells fabricated within this project (see solar cells with passivating contacts section), were also modelled in state-of-the-art Sentaurus TCAD framework. In Fig. 1, modelled dark saturation current density (J_0) as function of doping concentration and parameterized for different levels of surface recombination velocity (SRV) is reported. This diagram illustrates the concurrent action of chemical and electrical passivation. In fact, per each SRV ranging from *non-passivated* to *perfectly passivated* surface, the larger the doping concentration in the doped layer is, the lower the J_0 becomes. The modelling allowed to decouple these two effects and correctly predicted the performance of poly-Si layers at TUDelft. In addition, as shown in Fig. 2, the modelling of transport mechanisms across the tunneling SiO_2 revealed that a controlled dopants in-diffusion from the heavily-doped poly-Si to c-Si supports carrier collection and enhances the fill factor (FF) in solar cells endowed with such layers. Another important modelling activity was to assess the limit of the carrier transport in tunneling SiO_2 / poly-Si layers. It was found that in presence of current crowding (i.e. charge carriers travelling first in vertical direction and then changing laterally their direction to reach a metallic contact) the choice in using either n-type or p-type poly-Si layers essentially comes down to transport those charge carriers with the highest tunneling probability through the thin SiO_2. As electrons possess highest tunneling probability, in front-rear contacted solar cells (see solar cells with passivating contacts section) the usage of p-type poly-Si rear emitter is expected to favor higher conversion efficiency.

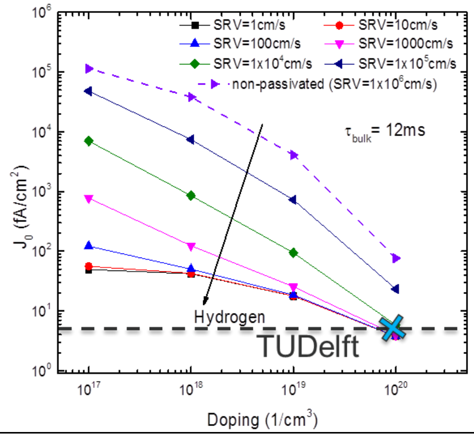

Fig. 1. Simulated dark saturation current density (J_0) of an n-type poly-Si layer as function of doping concentration and parameterized for different levels of surface recombination velocity (SRV).

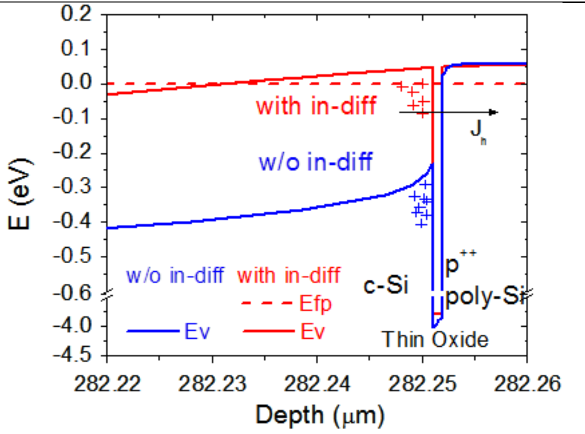

Fig. 2. Modelled band diagram around the interfaces c-Si / tunneling SiO_2 / p-type poly-Si without and with allowing boron atoms in-diffusion tail from the poly-Si layer to the bulk c-Si.

Novel surface passivating schemes

Atomic Layer Deposition (ALD) is a technology in which layer properties can optimally be tuned with respect to its required properties. It has been demonstrated that novel layer structures can be applied that result in excellent surface passivation.

Both TU/e and ASM carried out a brief market survey and technical assessment of ALD. The main conclusions are summarized below.

- ALD Al_2O_3 in general provides superior passivation with respect to Al_2O_3 from other deposition methods (e.g., PECVD, Sputtering).
- ALD is promising as high-throughput deposition technique, as thin layers are sufficient, with low TMA ($(CH_3)_3Al$) usage, high uniformity, and it provides excellent passivation. SiO_2/Al_2O_3 can be used for the passivation of both cell surfaces simultaneously, providing higher throughputs
    - To reduce or prevent back-side discoloration concerns (which appear on the front-side of a packaged cell) ASM has investigated the impact of thinner Al_2O_3 layers and of double sided depositions with respect to throughput and Cost of Ownership (CoO). As compared to the reference process at the start of the project, for single-sided depositions with <1mm discoloration at the backside significant throughput and CoO enhancements are possible without impacting the efficiency, while for double-sided deposition all CoO parameters can remain the same without discoloration.
    - An additional CoO benefit could be obtained by recipe optimization that went hand-in-hand with the above developments and has led to significant reductions of TMA consumption without impacting performance: TMA consumption is up to 4 times lower than with the previous ALD Al_2O_3 process of record, and typically 20 times lower than for competing PECVD Al_2O_3 processes.
- In the PV industry, PECVD is in particular competing with ALD as a deposition method for Al_2O_3, as PECVD reactors are already installed in most production lines for the subsequent deposition of SiN_x:H and holds a very strong foothold, whereas ALD is a relatively new technique in the field of PV manufacturing.
- Currently, it seems to be very difficult for ALD reactors to displace PECVD due to economic considerations, despite the obvious technological advantages of ALD.

Different and novel stacks for passivation were developed and characterized. Depending on surface properties (doping type, morphology) SiO_2/Al_2O_3 stacks were compared to single layer Al_2O_3. Furthermore, properties of ALD TiO_x layers were explored and these layers showed good surface passivation quality. The results are summarized below (see list of publications for more details).

- SiO_2/Al_2O_3 stacks outperform Al_2O_3 in passivating n^+ Si for all doping levels, while Al_2O_3 performs better than SiO_2/Al_2O_3 on p^+ Si for all doping levels. Thicker SiO_2 layers are preferred to passivate phosphorous-doped Si.
- The benefits of SiO_2/Al_2O_3 stacks are demonstrated on n^+ black Si surfaces.
- TiO_x prepared by ALD is an interesting new passivation material. Using a post deposition anneal, high lifetimes of ~1.4 ms can be obtained, showing good passivation.

To obtain good passivation cleaning of the interface surface and post-treatments (e.g. thermal anneals) are important. Especially processes to optimize the SiO_2 tunneling layer were investigated.

SiO_2 formation from de-ionized H_2O and from HNO_3 was studied for different oxidation times, temperatures and with different capping layers. The oxide is studied fundamentally, both for poly-Si emitters, and for TiO_x. As mentioned before excellent passivating results were obtained for structures based on poly-Si, and good passivation was reached for TiO_x.

Solar cells with passivating contacts

The feasibility of applying passivating contact structures for different interfaces and by different materials was carried out. Results were published (see list of publications) and summarized below.
At PVMD group (TUDelft), *lab-scale c-Si solar cells* endowed with carrier-selective passivating contacts were designed, fabricated and characterized. The studied embodiment for carrier-selective passivating contacts was based on tunneling SiO_x and ion-implanted poly-Si. The poly-Si layers were, like described in a previous section, applied using LPCVD. Two main solar cell architectures were devised: front-rear contacted (FRC) and interdigitated-back contacted (IBC). Further, the FRC cells were of two types and elaborated on the standard rear emitter n-PERT architecture: the Passivated Rear and Front ConTacts (**PeRFeCT**) cell and the **Poly-Poly** cell. In both cases, the bulk was n-type FZ c-Si wafer and the rear emitter was a p-type poly-Si passivating contact. The front surface field (FSF) was the element of differentiation between the two FRC types of cells. In the PeRFeCT cell, the FSF was a combination of full-area diffused or implanted n-type c-Si for high front transparency with n-type poly-Si only under the metallic contacts to quench surface recombination at metal/Si interface. In the Poly-Poly cell, the FSF was simply a full-area n-type poly-Si passivating contact. As for the IBC architecture, solar cells were also based on n-type FZ c-Si wafer but with both p-type and n-type poly-Si at the rear side in the role of rear emitter and back surface field, respectively. In **Poly-Si IBC** solar cells, the FSF was a lightly-doped n-type ion-implanted c-Si coated with an a-Si:H / SiN_x:H stack in the double role of passivation layers and anti-reflective coating. The table below (table 2) summarizes the best results obtained. Provided that the fill factor (FF) in FRC cells can be further improved, the PeRFeCT and the Poly-Poly cells clearly show the trade-off between parasitic absorption that impacts on short-circuit current density (J_{SC}) and surface passivation that impacts on open-circuit voltage (V_{OC}). FRC cells developed in this project allow for easy and industrially compatible processing (especially the Poly-Poly cell) and have a practical conversion efficiency outlook of more than 22.5%. The IBC cells based on poly-Si passivating contacts, in exchange of a somewhat longer fabrication process, combine both abovementioned aspects and realize also FF ~ 80% for large area (9 cm^2) devices. A practical conversion efficiency outlook of more than 23.5% is attainable with technology developed in this project.

Table 2: cell parameter of solar cells with different cell architectures

Cell architecture	Cell type	Area (cm^2)	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF (%)	η (%)
FRC	PeRFeCT (n - front text)[*]	7.84	656	40.7	75.2	20.1
	Poly-Poly (n - front text)[*]	7.84	682	38.1	75.2	19.5
IBC	Poly-Si IBC (n - text, FSF)	9.00	695	39.5	79.6	21.8
	Poly-Si IBC (n - text, FSF)[**]	0.72	709	40.7	76.6	22.1

[*] J_{SC} is corrected for 5% metal shading (aperture area), highest measured FF is 77.9% via screen printing.
[**] Highest measured FF is 83.2%

At ECN, in cooperation with ASM, the research focus was on the processing of large area solar cells. Besides Low Pressure Chemical Vapor Deposition (LPCVD) poly-Si layers, layers applied by Plasma Enhanced Chemical Vapor Deposition (PECVD) were investigated. Doping of B or P was carried out by adding B and P containing precursor gases to the SiH_4/H_2 mixture, which was used to deposit a thin amorphous Si layer. After depositions a post anneal was performed to create the poly-Si layers (crystallization). Both thermally grown SiO_2 and chemically grown SiO_2 layers were applied as tunnel oxide layers. All processing was carried out on textured 156x156 mm^2 n-type Cz wafer (243 cm^2). The hydrogenation step to terminate dangling bonds at interface (chemical passivation) was realized by applying a PECVD SiN_x:H layer. A standard industrial SiN_x:H layer was deposited for this purpose.

First the n-type and p-type doped poly-Si layers using PECVD were optimized. Doping level, temperature post-anneal, layer thickness, and growing the oxide were optimized to reach the best surface passivation. In table 3 the results are summarized for both p- and n-type poly-Si layers. As described above 156x156 mm^2 textured n-type Cz wafers were used and a standard SiN_x:H was applied as well. Best results were obtained n-type poly-Si layers. Values above 730 mV demonstrate excellent passivation! The layers have a thickness of 20-40 nm and the active dopant concentration is $>10^{20}$ cm^{-3}. Differences between 20 and 40nm thick layers were negligible.

Table 3: Best implied V_{OC} values for differently doped poly-Si layers applied to large area textured n-type Cz wafers

PECVD layers	i-V_{OC} (mV) with thermal oxide	i-V_{OC} (mV) with chemical oxide
n-type poly-Si	736	732
p-type poly-Si	706	679

ASM and ECN also optimized the process for LPCVD poly-Si layers on large area wafers. Both in-situ and ex-situ doping was carried out. Only n-type poly-Si were applied for this optimization. Layers with varying thickness were used. A post-anneal was performed for the in-situ doped layers. For the ex-situ doped layers, the P diffusion can be seen as the post treatment. Again SiN_x:H was applied for obtaining the best passivation. A thermally grown SiO_2 layer was applied as tunnel oxide. The results are summarized in table 4. From the table it can be concluded that for this experiment ex-situ doping gave the best results: excellent passivation (i-V_{OC}>730 mV) has been reached with LPCVD layers. For in-situ doped layers implied V_{OC} values close to 690 mV were obtained, demonstrating reasonable good passivation. However, transportation of in-situ doped layers could affect the passivating quality for the in-situ doped layers, and therefore resulting in lower i-V_{OC} values.

Table 4: Implied V_{OC} for LPCVD layers deposited at ASM. Doping was carried out in-situ or ex-situ.

Thickness poly-Si (nm)	i-V_{OC} (mV) in-situ doped	i-V_{OC} (mV) ex-situ doped
20	669	730
40	680	733
100	685	731

Completed large area (156x156 mm^2) solar cells were made in cooperation with ECN's TANGO project (internal project ECN) using the following process steps: texturization of the n-type Cz wafer, thermally grown SiO_2 tunnel oxide, in-situ doped PECVD layers front (p-type) and rear (n-type), anneal, PECVD SiN_x:H for passivation, removal SiN_x:H, In doped SnO_2 (ITO) transparent conductive oxide (TCO) front and rear, screen-printed front and rear Ag metallization. The thickness of the poly-Si layers was 40 nm. The cell structure is very similar to the PeRFeCT cell described in the previous section, which were made at TUDelft. Main differences are the ITO layers and screen-printed metallization. The TCO layer will result in additional parasitic absorption, which will reduce the short circuit current density J_{SC}. The best cell parameters of a batch of solar cells is summarized in table 5. The conversion efficiency η was determined using the ECN I/V measurement setup. Data were not corrected for spectral mismatch. Combining the best V_{OC}, J_{SC} and FF should result in 18.8% efficiency. The most important parameter that shows the quality of the passivation is V_{OC}. Since the best values for completed cells are close to 700 mV, we can state that the passivation quality is still good after finishing the solar cells. Of course final optimization of the process should result in even better values, especially for J_{SC} and FF.

Table 5: Best cell parameters from a batch of cells.

Best parameters	V_{OC} (mV)	J_{SC} (mA/cm2)	FF(%)	η (%)
	694	35.8	75.6	18.0

Towards ultra-thin solar cells

At the beginning of the project several companies were able to manufacture ultra-thin wafer material, also called Si foils. Unfortunately, during the project the material was not available anymore (due to bankruptcy).

However, based on the processing carried out on commercially available thicker wafers (180 µm) we are able to make some remarks what to expect by applying poly-Si layers to Si foils.

Polysilicon layers were deposited on both sides of test wafers, using methods that are compatible with processing of ultra-thin wafers, by placing them horizontally on a supporting surface during deposition. The results were promising for PV applications. An implied V_{OC} of 733 mV was achieved for ex-situ doped (by $POCl_3$ diffusion) 20 and 40 nm thick polysilicon layers deposited with the vertical stack LPCVD furnace at ASM. In-situ doped LPCVD samples from ASM performed less with a maximum at 685 mV, however, the in-situ doping recipe was not yet optimized and can be improved. For comparison, also samples with 20 and 40 nm polysilicon layers on both sides were deposited in a pilot R&R PECVD system (also horizontally placed). After crystallization of the layers, also good values were found for this approach with a maximum in implied V_{OC} of 721 mV.

These experiments demonstrate that good passivation can be obtained with horizontally processed wafers. This horizontal processing is compatible with processing of silicon foil material. For the conventional tube system processing the wafers are processes vertically and because of the flexibility of the wafers and it will possible the wafers, positioned oppositely, bow and touch each other.

Conclusions and recommendations

Although a small change in the work plan was made, which could be explained by the fast evolving market (both industrial and R&D) we can conclude that all main objectives were reached.

Processes for doped poly-Si layers compatible with high-volume processing were successfully developed. Both on labs systems and industrial systems excellent passivating contacts based on poly-Si were obtained. Furthermore high-quality poly-Si layers were processed for both polarity and for both planar and textured surface. Ion implantation, ex-suti $POCl_3$ diffusion and in-situ doping processes were applied.

Novel passivating surfaces based on ALD of metal oxides were explored and the fundamental mechanisms of surface passivation are understood. Also the effect of post-annealing on the passivation quality was evaluated. All processes for novel passivating contacts are compatible with high-volume manufacturing technologies.

Solar cells with passivating contact and efficiencies above 20% were made. For cells with contacts on both sides the efficiency (active area) was just above 20%, while for back-contacted cells an efficiency above 22% was reached, to our knowledge the best efficiency for silicon cells completely processed in the Netherlands. Furthermore, V_{OC} and J_{SC} are compatible with cells with efficiency of 23.5%. Also processing large area industrial cells resulted in very good V_{OC} values demonstrating the good surface passivation can be maintained.

For processing suitable for **ultrathin solar cells** horizontal processing seems to be the best way to continue. Both the systems at ASM and ECN have a layout for horizontal processing. Because excellent passivation is obtained with this processing it is expected the same results can be reached on silicon foil material, which was unfortunately not available during the project.

Project management

The project was carried out by ASM (coordinator), TUD, TU/e and ECN. Most of the research work was carried out according to the plan, and all main expected results and milestones were achieved.

Because of the fast developments in this highly competitive market with a huge pressure on cost, it was not possible to test processes developed on a larger scale. On the other hand principal developments were carried out on full size industrial wafers (156x156 mm^2) and industrial equipment using low-cost processing such as screen-printing. Another aspect that changed during the project period is the focus on passivating and carrier selective contact. In the beginning of the project ion implantation for so-called homojunctions followed by a thermal anneal / activation looked as a promising technology. However, the introduction of ion implantation for general homojunctions lost interest. Therefore the focus of the project changed towards doped poly-Si layers, and doping was carried out by ion implantation.

In the original budget of the project ASM expected to spend much more on equipment depreciation and less on engineering resources. During the project this changed and the expenses on equipment depreciation were limited, but contrary, the expenses for engineering resources on R&D doubled compared to the original budget. Overall the expenses for ASM reduced significantly from the original expectations. As a result ASM did not apply for maximum subsidy and its contribution was largely in-kind, to ensure the industry contribution to the project remained above 20%.
Furthermore, an extension of the project by six months was applied for, and granted.
Besides regular telephone conferences and frequent e-mail exchanges to discuss the progress, twice a year face to face meetings were organized in which results were exchanged and novel experiments were set up.

List of publications

Conferences / proceeding papers

- B.W.H. van de Loo et al., “Understanding and reducing charge-carrier recombination at passivated and highly-doped Si surfaces”, 5th Silicon PV conference, Konstanz, Germany, 2015
- J. Melskens et al., “Concepts and prospects of passivating contacts for crystalline silicon solar cells”, 42nd IEEE PVSC, New Orleans, LA, USA, 2015
- J. Melskens et al., “Concepts and prospects of passivated contacts for crystalline silicon solar cells”, 31st EU-PVSEC, Hamburg, 2015
- B.W.H. van de Loo et al., “The Influence of Doped Regions and Passivation Layers on the Surface Recombination in Silicon Solar Cells”, 31st EU-PVSEC Hamburg, Germany, 2015
- B.W.H. van de Loo et al., “ALD SiO_2/Al_2O_3 stacks for the passivation of phosphorus-doped black-Si surfaces”, 6th Silicon PV conference, Chambery, France, 2016
- J. Melskens et al., “Feasibility study of titanium dioxide as passivating electron-selective contact for crystalline silicon solar cells”, 6th Silicon PV conference, Chambery, France, 2016
- B.W.H. van de Loo et al., “Atomic-Layer Deposited Passivation Schemes for c-Si Solar Cells”, 43rd IEEE PVSC, Portland, 2016
- B. Macco et al.,” Status and Prospects for Atomic Layer Deposited Metal Oxide Thin Films in Passivating Contacts for c-Si Photovoltaics”, 43rd IEEE PVSC, Portland, 2016
- J. Melskens et al., “Titanium oxide: a promising candidate material as electron-selective passivating contact for crystalline silicon solar cells?”, 32nd EU-PVSEC, Munich, 2016
- G. Yang, N. van Hameren, A. Ingenito, O. Isabella, M. Zeman, *Ion-implanted poly-crystalline silicon passivating contacts for high efficient c-Si IBC solar cells*, 5th International Conference on Silicon Photovoltaics, Konstanz (2015).
- A. Ingenito, G. Yang, O. Isabella, M. Zeman, *Progress towards highly efficient IBC cells at Delft University of Technology*, 7th Workshop on Back Contacted Solar Cells, Freiburg (2015).
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- A. Ingenito, H. Dijkslag, G. Yang, O. Isabella, M. Zeman, *n-PERC c-Si solar cell architecture with front and rear ion-implanted carrier-selective contacts*, 32nd European Photovoltaic Solar Energy Conference, Münich (2016).
- G. Yang, A. Ingenito, G. Limodio, O. Isabella, M. Zeman, *IBC c-Si solar cells based on ion-implanted poly-silicon passivating contacts*, 26th Photovoltaic Science and Engineering Conference, Singapore (2016).
- G. Limodio, G. Yang, A. Ingenito, A. W. Weeber, O. Isabella, M. Zeman, *Implantation-based c-Si passivating rear and front contacts (PeRFeCT) solar cell*, 7th International Conference on Silicon Photovoltaics, Freiburg (2017).
- G. Yang, P. P. Moya, Y. Zhang, A. Ingenito, G. Limodio, A. Weeber, O. Isabella, M. Zeman, *IBC c-Si Solar Cell with Poly-Si(O_x) Passivating Contacts*, 7th International Conference on Silicon Photovoltaics, Freiburg (2017).
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Nederlandstalige samenvatting

Dit project werd uitgevoerd door ASM, TU/e, TUD en ECN en had tot doel eigenschappen van zogenaamde passiverende contacten te begrijpen, goede passivering te bereiken en uiteindelijk deze nieuwe lagen op zonnecellen toe te passen.

Allereerst is de passivering van structuren op basis van poly-Si onderzocht en zijn verschillende depositie-technieken toegepast om dotering aan te brengen geëvalueerd. Ook zijn nieuwe lagen op basis van metaaloxiden en gedeponeerd met atoomlaagdepositie onderzocht. Met lagen gebaseerd op boor en fosfor gedoteerd poly-Si op een dun tunnel SiO_2 laagje is excellente passivering bereikt. Dit is aangetoond door implied V_{OC} waarden van boven 700 mV, en voor fosfor gedoteerd zelfs boven 730 mV. Deze hoge waarden zijn tevens bereikt op grote industriële silicium plakken met een oppervlakte textuur (dus een groter effectief oppervlak dan vlakke wafers). Ook is processing toegepast die geschikt is voor grootschalige productie.

Atoomlaag depositie van nieuwe metaaloxide lagen biedt mogelijkheden om het rendement te verhogen en de celprocessing te vereenvoudigen, dus op termijn mogelijk resulterend in lagere kosten. Zeer goede passivering is bereikt voor Al_2O_3, en voor een dubbellaag SiO_2/Al_2O_3 zelfs een betere passivering. Atoomlaagdepositie is een technologie die geschikt is om grootschalig toe te passen en uitermate geschikt om oppervlakken met ruwe structuur (bijvoorbeeld het zogenaamde black silicon) te passiveren (ook aangetoond binnen dit project). Over passiverende lagen aangebracht met atoomlaagdepositie is een hoofdstuk van een boek geschreven.

Tenslotte zijn complete zonnecellen gemaakt met deze zogenaamde passiverende contacten. Voor laboratorium cellen met contacten op voor- en achterzijde zijn rendementen van boven 20% behaald (open area efficiency). Op grote industriële cellen waren de rendementen iets lager, maar zijn eveneens hoge V_{OC} waarden bereikt. Dit laatste toont aan dat ook op complete cellen de passiverende werking van de poly-silicium lagen nauwelijks minder wordt. Op laboratorium cellen met alle contacten aan de achterzijde zijn rendementen van boven 22% behaald (bij ons weten de beste cellen compleet gemaakt in Nederland). De V_{OC} en J_{SC} waarden zijn zelfs compatibel met rendementen van 23.5%

Omdat zowel op niveau van lagen goede passivering bereikt is, als ook rendementen boven 22% behaald zijn, kan geconcludeerd worden dat het project succesvol afgesloten is.

Projectmatig gezien is gedurende het project een aangepast werkplan gemaakt. Door de snelle ontwikkeling in de markt (zowel commercieel als binnen R&D) was deze aanpassing nodig en konden wij meer inzetten op de huidige nieuwe technologieën. Mede daarom zijn de goede resultaten op passivering behaald wat essentieel is voor toekomstige hoog-rendement silicium zonnecellen.

Verkrijgbaarheid dit openbare rapport

Dit rapport is aan te vragen bij ASM (hessel.sprey@asm.com) en bij ECN (weeber@ecn.nl).

Afzonderlijke publicaties (zie lijst van publicaties) zijn verkrijgbaar via uitgevers.