Rijksdienst voor Ondernemend Nederland

Openbaar eindrapport Momentum

Gegevens project

- Projectnummer: 1821101
- Projecttitel: MOMENTUM (Metal Oxides: Maturing of an Efficient Novel Technology Upgrade for PV-Manufacturing)
- Penvoerder en medeaanvragers: TNO (Penvoerder), TU Eindhoven, TU Delft, Solmates B.V., Levitech B. V.
- Projectperiode: 01/02/2020-30/06/2022
- Publicatiedatum openbaar rapport: 30/08/2022

Samenvatting van uitgangspunten, doelstelling en samenwerkende partijen

Background: Excellent passivating contacts can be made based on doped silicon and silicon alloys, either a-Si:H or poly-Si. However, the limited transparency of these contacts induces absorption losses at the front side, or restricts their use to the rear side of the cell. This limitation has initiated many investigations on more advanced, often inherently also more expensive, front side processing steps. These include looking into advanced metallization, selective or deep emitters or switch to more complex interdigitated back contact (IBC) patterning of doped poly-Si contacts at the rear side of the cells.

Since 2013, novel passivating contact materials based on transition metal oxides (TMOs), like MoOx and TiOx, have been emerging as well as a wide variety of other materials. Passivating contacts form full-area surface passivation, which leads to high cell voltages. Moreover, cells with TMO based passivating contacts display high transparency and enable low-cost processing compared to their silicon-based counterparts. This makes these structures uniquely suited for the front side. However, more R&D is required to exploit their full potential towards >25% efficient solar cells.

Objectives: In MOMENTUM we have built upon previous achievements that clearly showed the high-efficiency potential and simple, short process flow of these passivating contacts. For the MoOx based hole-selective contact (WP1), a key aspect is to achieve good understanding of the interactions between the different layers. It was previously found that the interface damage on the surfaces is mostly related to the large e-beam and sputtering processes that were used for the deposition of MoOx and transparent conducting oxide (TCO). In this project we have used the pulsed laser deposition (PLD) tool from Solmates which enables an inherently 'softer' deposition process for TMOs and TCOs on 6-inch wafers. We have also used an integral approach, in which variations of the different layers were optimized in the full contact stack. For example, different routes to make a thin and well passivating interfacial oxide was tested directly in combination with PLD MoOx layers and TCOs. Also, further tuning of the process recipes for deposition of the PLD layers is required to achieve good control of the selective properties of MoOx and the transparency and conductivity of the TCO.

Promising results were achieved in the previous TKI projects in testing ALD TMO layers for the electron-selective contact. Very thin layers of TiOx were identified as excellent candidates for this contact, based on their good passivation properties and low contact resistance. However, with respect to contacting there are still some challenges for these layers to be implemented as transparent contacts in high-efficiency solar cells. For the TiOx based electron-selective contact (WP2) other aspects are crucial, in particular realizing a successful combination with a TCO, while maintaining good passivation and selectivity is important. To this purpose, the route of implementing a thin ALD buffer layer below a TCO was explored, in combination with further improvements of the TiOx deposition process and the interfacial oxide.

The PLD and ALD processes that are developed in MOMENTUM, will be available on pilot equipment at TNO and are compatible with 6-inch wafers and upscaling to higher throughput equipment. In future, they will allow for high efficiency bifacial solar cells with a simple manufacturing process. In MOMENTUM the electron- and hole-selective contacts were optimized separately with a doped poly-Si based rear contact. Next step would be to have an elegant full TMO concept.

Collaborating parties: TNO performed dedicated research development and control of the properties of PLD based passivating contacts. TNO looked into the effects of various interlayers in combination with the PLD deposited passivating contacts. Solmates played an essential role in placement and process support of the PLD cluster tool at TNO, which is used for development of low-damage MoOx layers, TiOx layers, and transparent conductive oxides (TCOs). Levitech supported optimization of the Levitrack process for deposition of Al2O3 as a passivating interlayer in selective contacts and evaluated implementation of the novel ALD processes developed by TU/e. This included an ALD buffer layer that enables the use of TCO on TiOx. TUD provided reference lab processes on a-Si:H interlayers and worked on alternative oxide interlayers.

Beschrijving van de behaalde resultaten, de knelpunten en het perspectief voor toepassing

- WP1: MoOx based hole-selective contact:
    - At TNO, variations of MoOx thin films depositions were performed with e-beam as a reference to define the important work function parameters
    - At TUD, the MoOx/a-Si:H hole transport stack was improved with optimizations on thermally evaporated MoOx thickness in combination with plasma treatment at i-a-Si:H/MoOx interface and metalization via Cu-plating. Record efficiency of 23.83% was achieved on ~4 cm^2 cell area with V_{oc}=721 mV. This was independently certified on 13/January/2022.
    - Joint work between TNO and Solmates on developing PLD MoOx recipe. The depositions were done on a-Si, thin Al_2O_3 and thin SiO_x interlayers. The first results showed some damage upon the deposition. This was mostly mitigated by optimizing the recipe. Lifetimes up to 2 ms were achieved.
- WP2: TiOx based electron-selective contact:
    - Reestablishment and verification of TiOx ALD process. The passivation quality of the ALD TiOx is on-par with state-of-the-art TiOx on c-Si (~1 ms). Further optimization of TiOx layers combined with i-aSi:H will be done in joint experiment TU/e-TUD.
    - Joint experiment TU/e-TUD on ALD TiOx on i-aSi:H passivation layer. HPT was applied to recover the passivation after the TiOx deposition. Sputtering of TCO layer leads to degradation that can be partially recovered after post-deposition annealing.
    - After modifications to the Levitrack, successful ALD depositions have been conducted for novel n-type contacts. Joint experiments TU/e-Levitech demonstrate that TiOx can be cleaned which enables quick maintenance in the ALD production tool.
- Extra results:
    - Joint experiment TU/e-TUD on integration of both MoOx and TiOx in solar cell. First devices were fabricated with various TiOx/metal contacts with 17.7% efficiency (V_{oc} limited). Further tests to control passivation are ongoing.
    - Joint work TNO/Solmates on developing ITO recipe. The ITO process was optimized on Si and on glass at temperatures up to 600 °C. Rsheet values as low as 20 ohm.sq were obtained.
    - Installation of a unique PLD tool with capability of deposition at temperatures up to 600 °C, in-situ annealing, and multi target loading. This tool is capable of automatically running a full cassette (25 wafers) of 6 inch Si wafers through a robot handler without a vacuum break. This is an important step towards processing TMO cells in an industrial setting and for higher TRLs.
- Bottlenecks
    - COVID-19: some delays in performing the experiments, availability of personnel, delivery of parts and opening of the labs happened due to the pandemic.
    - Delay in the completion and operation of PLD system at TNO. This caused delays in the progress of the PLD developed processes and integration of all transparent oxide films into 6 inch solar cells.

The results achieved in this project can enable manufacturing processes for highly passivating and selective MoOx and TiOx based passivating contacts on 6-inch wafers, using the industrial pilot tools present. This in the near future can lead to conversion efficiency values higher than 25%.

In this consortium, improved control and understanding of the interactions between the different layers in TMO-based passivating contacts and knowledge on ways to scale this technology to 6-inch wafers was achieved. These developments will provide a competitive edge in the international c-Si PV R&D field for the Dutch industrial partners in the form of IP and publications. The technology developed in this project was carried out on all aspects from TRL level 2 (technology concept) to TRL level 4 (validation in laboratory). This can further developed into higher scale manufacturing processes and higher TRL levels.

Beschrijving van de bijdrage van het project aan de doelstellingen van de regeling (duurzame energiehuishouding, versterking van de kennispositie)

By developing industrially compatible, high-efficiency heterojunction solar cells, based on a short and simple process flow, using Dutch processing equipment, we cover a large part of both the overall ambitions of the TKI Urban Energy and Programme line 1a (zonnestroomtechnologie). Program line 1a aims to reduce the production costs of PV panels for large scale generation and a guaranteed lifetime of 30 years in 2020. For mainstream silicon PV technology this target has been achieved for solar panels by many manufacturers using passivated emitter rear contact (PERC) technology. However, calculations made in our former contribution in a TKI project (the RADAR project) pointed out that reducing the number of process steps, as can be achieved by making a cell with two TMO contacts (MoTi cells in Fig. 1), without introduction of high cost of ownership (CoO) tools, like the high vacuum PECVD system that is needed for SHJ solar cells, will enable solar panel manufacturing costs that are comparable to those of PERC.

Additionally, for efficiencies above 23% more advanced processing is needed for PERC (PERC+ in Fig. 1), while for cells with two TMO contacts such efficiencies are within reach by optimization of the layer properties only. So for MoTi cells with efficiencies above ~22%, costs can be lower in comparison to PERC. Although individual process steps may at the start be more expensive for MoTi when compared to PERC, the short process flow strongly reduces costs of e.g. floorspace, yield loss and downtime losses, keeping the overall costs low, as is illustrated by the right graph in Figure 1. It should be noted that the cost calculations have been done at the start of the project and the absolute numbers have been reduced in the past few years. However, the relative costs are still valid.

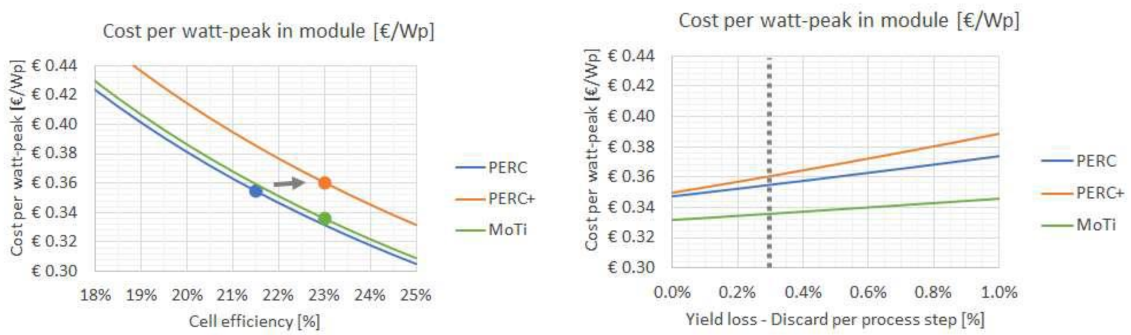

Figure 1: Cost estimates from the RADAR project. Absolute numbers may vary for specific locations, but the largest differences between the trends are related to the number of tools required for the process, which is 6 for MoTi cells and 11-15 for PERC(+) cells. This is reflected in the overall yield loss, the cost of ownership (CoO) and in the floorspace and depreciation costs and are expected to scale with local prizing, due to which the relative differences will remain. Left: Estimates of cost per Wp for bifacial PERC (uniform emitter) and PERC+ (selective emitter) and bifacial MoTi cell as a function of solar cell efficiency. The arrow indicates the efficiency range in which a transition from a simple to a more complex solar cell process is required. Right: Dependence of cost/Wp on yield loss for assumed efficiencies of 21.5%, 23% and 23%, respectively (indicated by dots in the right graph).

Upgrades of process lines for main stream solar cell technology that use only parts of the results of this project, e.g. only the hole- or the electron-selective contact, can lead to an increase in revenue for the Dutch partners. The contacts can be applied both on p-type and n-type wafers and, due to their transparent nature, they can equally viably be applied on the front and rear side of the cell. Furthermore, because of oxide-based surface passivation, the technology is also expected to be less sensitive to impurities than SHJ contacts, which makes them more compatible with existing production lines. Use of the results as enabling upgrades of existing cell technology, was the reason to focus for each of the deposition techniques on just one of the selective contact layer stacks. The processes developed in MOMENTUM can be transferred step-by-step to industry, which enhances the economic impact of the project. For example, the hole-selective layers can be applied to the front of current Topcon solar cells as a more transparent alternative to a diffused boron emitter. Not only the efficiency will increase this way, but the cells and modules can also more easily be made bifacial. TOPCon-like cells were made as test structures in this project to optimize the TMO layers, in which the TMO layers replace the surface diffusions, but these can serve at the same time as a showcase for equipment manufacturers working on these more mainstream types of devices.

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Spin off binnen en buiten de sector

Dutch R&D has been able to keep up with the global trends in TMO passivating contact technology. Because of the growing market, better economic opportunities and a rising demand for higher efficiencies, the market perspective for new technology will improve and create openings for high efficiency technologies like the Moly-TiO_x (MoTi) cells developed in this project. The whole market, from manufacturers to PV installing companies, from equipment vendors to engineering companies, and finally the end-user (consumers) will profit because of improved margins and lower LCoE. Dutch equipment suppliers will benefit even more, because of their better knowledge position.

Overzicht van openbare publicaties over het project en waar deze te vinden of te verkrijgen zijn

1. L. Mazzarella *et al*. patent PCT/NL2025744
2. L. Mazzarella *et al*., "Strategy to mitigate the dipole interfacial states in (i)a-Si:H/MoOx passivating contacts solar cells," *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, 2020, pp. 0405-0407. https://ieeexplore.ieee.org/document/9300968
3. L. Mazzarella *et al*., Strategy to mitigate the dipole interfacial states in (i)a-Si:H/ MoOx passivating contacts solar cells. Prog Photovolt Res Appl. 2020;1–10. https://onlinelibrary.wiley.com/doi/10.1002/pip.3381
4. L. Cao *et al*., "The application of ultra-thin MoOx in silicon heterojunction solar cells," oral presentation. MRS Fall Meeting & Exhibit, Boston, (2021) https://www.mrs.org/docs/default-source/meetings-events/fall-meetings/2021/abstract-book.pdf?sfvrsn=64f2160f_3
5. L. Cao *et al*., "Interface treatment for high efficient dopant free MoOx silicon heterojunction solar cells," accepted as oral presentation by 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Milan, (2022)
6. L. Cao *et al*., "Achieving 23.83% conversion efficiency in silicon heterojunction solar cell with ultra-thin MoO_x hole collector layer via tailoring (*i*)a-Si:H/MoO_x interface", submitted to Progress in Photovoltaics: Research and Applications, invited paper(2022)
7. L. Cao *et al*., "The application of ultra-thin MoO_x in silicon heterojunction solar cells", submitted to Asian PVSEC, Nagoya, (2022)
8. L. Cao *et al*., "Interface treatments for high-efficiency MoOx based silicon heterojunction solar cells", submitted to MRS Fall Meeting, Boston, (2022)
9. R.J. Theeuwes, J. Melskens, L.E. Black, W. Beyer, D. Koushik, W.J.H. Berghuis, B. Macco, and W.M.M. Kessels, POx/Al2O3 Stacks for c-Si Surface Passivation: Material and Interface Properties (https://pubs.acs.org/doi/full/10.1021/acsaelm.1c00516)
10. R.J. Theeuwes, J. Melskens, W. Beyer, U. Breuer, L.E. Black, W.J.H. Berghuis, B. Macco, and W.M.M. Kessels, POx/Al2O3 stacks for surface passivation of Si and InP, Submitted.
11. R. J. Theeuwes, J. Melskens, L. E. Black, W. Beyer, U. Breuer, W. J. H. Berghuis, B. Macco, W. M. M. Kessels, Excellent Surface Passivation of Textured n+-doped Silicon by POx/Al2O3 Stacks https://www.siliconpv.com/program/siliconpv-2022-awards
12. R. J. Theeuwes, J. Melskens, L. E. Black, W. Beyer, U. Breuer, W. J. H. Berghuis, B. Macco, W. M. M. Kessels, Excellent Surface Passivation of n+-doped Silicon by POx/Al2O3 Stacks with High Positive Fixed Charge Density,) MRS Spring 2022, https://www.mrs.org/meetings-events/spring-meetings-exhibits/2022-mrs-spring-meeting/symposium-sessions/symposium-sessions-detail/2022_mrs_spring_meeting/en01 (EN01.03.03)
13. R.J. Theeuwes et al. - Excellent Surface Passivation of n+-doped Silicon by POx/Al2O3 Stacks with High Positive Fixed Charge Density (Oral presentation) (Won the Best Oral Presentation Award of the EN01 Silicon for Photovoltaics symposium)
14. Interview with Solar Magazine; Pulsed Laser Deposition gaat zonnepaneel van de toekomst opleveren. Het doel is een industriële cel-efficiency van meer dan 25%
15. Effects of Post Deposition Anneal on a Tunnelling Al2O3 Interlayer for MoOx hole selective contacts, Poster Presentation SiliconPV Conference 2021
16. M. A. Sen, P Bronsveld, A Weeber, Solar Energy Materials and Solar Cells 230, 111139, Thermally stable MoOx hole selective contact with Al2O3 interlayer for industrial size silicon solar cells, https://www.sciencedirect.com/science/article/pii/S0927024821001811
17. M. A. Sen et al., Influence of passivating interlayers on the carrier selectivity of MoOx contacts for c-Si solar cells, Paper submitted to Solar Energy Materials and Solar cells 2022.

18. M.A. Sen et al., Hydrogenated SiOy interlayer formed by etching Al2O3 for MoOx hole-selective contact, Poster presentation WCPEC-38 2022

Meer exemplaren van dit rapport

Meer exemplaren van dit rapport kunnen digitaal worden verkregen via het hieronder genoemde contact.

Contact voor meer informatie

Meer informatie over dit project kan verkregen worden via:

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Subsidie

Vermelding van de verkregen subsidie op de volgende manier:

Vanaf verlening 2014 (vanaf 11 juli 2014): *"Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland."*