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Optical Analysis of Perovskite/Silicon Tandem Solar Cells: Effect of Rear Side Grating and TOPCon Tunnel Junction

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Abstract. In the focus of the presented work is the analysis of a rear side reflection grating in context of a perovskite/silicon tandem solar cell. The typical configuration of a perovskite/Si tandem device requires a hole transport layer at the rear side of the silicon solar cell (p-i-n bottom cell structure). As such a poly-Si passivating contact like TOPCon is an attractive candidate. Until now, research faces the challenge to deposit p-TOPCon layers with good surface passivation properties on textured surfaces. A planar surface would avoid this issue and due to its smaller surface area intrinsically allowing for a better passivation. The optical disadvantage of the planar rear side can be eliminated by an appropriate optical grating at the rear side which enables ideal light trapping. In this work a new approach is developed to describe the optical properties of a diffraction grating as structured rear side reflector in a silicon bottom cell. The light distribution and the parasitic absorption per grating interaction are fitted to reflectance and absorptance measurements of a III-V on silicon triple-junction device with a rear grating structure. Compared to previous models, this new approach makes it possible to reliably quantify the different loss mechanisms in the spectral region above 1000 nm. An application of the simulation model to a perovskite/silicon tandem device shows the potential of the system with rear side grating. In addition, an integration of a TOPCon tunnel junction is evaluated and a process chain for the integration of a structured rear side reflector into the tandem system is discussed.

Keywords: Perovskite, Tandem Solar Cells, Grating, Light Trapping, TOPCon, poly-Si, Tunnel Junction, Renewable Energy, Photovoltaic

1. Introduction

Multi-junction solar cells offer the possibility to overcome the theoretical efficiency limit of silicon solar cells. One outstanding example of this technology is the triple junction with an efficiency of 35.9% presented in [1]. In this system two III-V solar cells are wafer-bonded on top of a silicon bottom cell and operate as 2-terminal device. The bottom cell has a TOPCon passivating contact at both interfaces (TOPCon^2) and its light trapping properties are enhanced by a photonic rear side grating. From an industrial point of view TOPCon is one of the most promising technologies for future photovoltaic applications [2]. Hence, a detailed analysis of this system is of special interest.

The aim of the present work is a detailed analysis of losses in the spectral region between 1000 nm and 1200 nm to describe the optical performance of the structured rear side reflector in perovskite silicon tandem solar cells. A simulation model is built to assess parasitic absorption at every rear side interaction, as well as parasitic absorption in the top cell materials and escape losses. A comparison with reflection and parasitic absorption measurements of a III-V//Si device [3] is used to fit the model´s free parameters. The developed simulation model is then transferred to a perovskite/silicon tandem solar cell to demonstrate the light harvesting properties of the grating in this new application. A comparison with a planar back reflector and random pyramids is performed to evaluate the performance of the grating. The integration of a TOPCon tunnel junction as interconnection between the perovskite top cell and the silicon bottom cell is discussed as well.

2. Optical simulations of a III-V on silicon solar cell

In the presented study we describe a simplified version of the system reported in [1]. The OPTOS formalism [4] is used to combine the light propagation along both surfaces with the incoherent propagation in the $300\ \mu m$ thick silicon bulk material. Therefore, the light distribution of each surface is described with a matrix. The front side escape loss is approximated with the condition that all light propagating under an angle larger than the angle of total reflection at a silicon air interface is trapped in the solar cell and the other part of light escapes. This approximation neglects the parasitic absorption in all top cell layers. The optical simulations of the structured rear reflector were performed with rigorous coupled wave analysis. A special challenge is the modelling of the structured metal grating due to the required high computational resources. As approximation, the grating is modelled with dielectric materials and planar rear reflector while maintaining the original period of $1\ \mu m$. Our approximation consists of a structured silicon grating planarized with the photoresist SU8, and a planar silver mirror at the rear. Due to the refractive index contrast between Si and SU8, the diffractive nature of the modeled rear side reflector is preserved ensuring a feasible computational effort, similar to the approach presented in [5]. For a better fit between model and experiment an additional parameter A_{para} is included to describe a constant parasitic absorptance per rear side interaction. This parameter accounts for the higher parasitic absorption at the experimentally realised structured metal rear reflector in comparison to the simulated dielectric rear reflector. For the best possible description of the real system, the model is fitted to match the reflectance R_{meas} and the parasitic absorptance $A_{\text{meas}} = 1 - EQE - R_{\text{meas}}$ of the III-V//Si tandem cell.

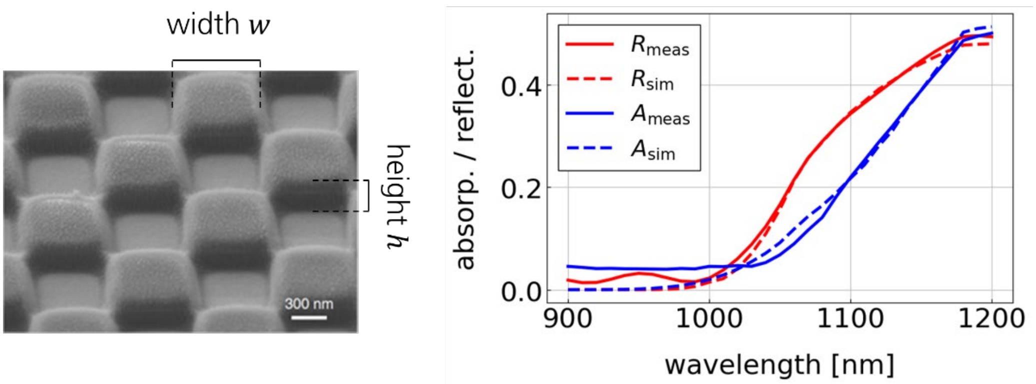

Figure 1. On the left side a SEM image shows a grating structure, the system parameters width w and height h are illustrated. On the right side reflection R_{meas} and parasitic absorption A_{meas} of the triple junction solar cell together with the calculated reflection and absorption from the established simulation model are plotted.

Therefore, the grating properties height h and width w (illustrated in FIG. 1 a) as well as the additional absorptance A_{para} are varied over a wide range. The best approximation is found for a grating height of $h = 175\ nm$ with a width of $w = 590\ nm$ and $A_{\text{para}} = 11\%$. The simulation results for the reflectance and parasitic absorptance are plotted in FIG. 1 b) together with the measured data and show a very good agreement.

The loss mechanisms of parasitic absorptance and escape are now well described by the model and result in an escape current density loss of $2.17\ mA/cm^2$, and a total parasitic absorption loss of $1.75\ mA/cm^2$, which includes free-carrier absorption in the highly doped silicon layers and parasitic absorption at the structured metal surface.

3. Transfer to perovskite/silicon tandem

The first step towards the integration of the structured back reflector in the perovskite/silicon tandem system is the transfer of the simulation model. Therefore, the front side in the model is changed to describe the perovskite stack depicted in FIG. 2. For the modelling, a perovskite of the composition CsFAPbIBr [6] with a band gap of $1.64\ eV$ is chosen and the silicon bottom cell is treated as $200\ \mu m$ thick bulk material. On the rear side, three different light trapping schemes are investigated. The three different systems are illustrated in Fig. 2.

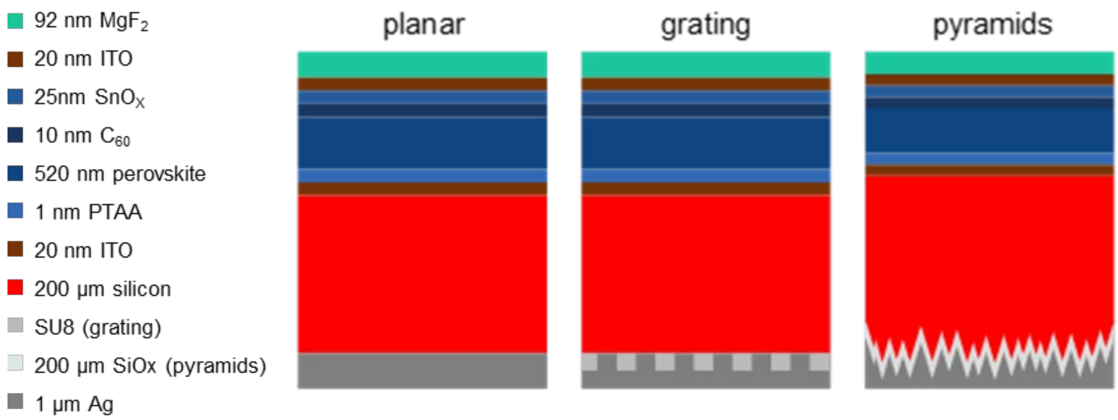

Figure 2. Illustration of the three compared systems (planar, grating, and pyramidal rear side). Materials and thicknesses of the layer stack are listed on the left side. The silicon solar cell is simulated as 200 µm thick bulk material.

4. Current gain comparison with different rear side structures

The light distribution in the system with planar rear side is illustrated in FIG.3 for an optimal perovskite layer thickness of $520\ nm$, guaranteeing current matching. The simulation results in a photocurrent density of $18.63\ mA/cm^2$ in current match conditions under the AM1.5g spectrum [7].

In the second plot the light trapping properties of a system with rear side grating are illustrated. Further, different loss mechanisms can be quantified and result in $1.79\ mA/cm^2$ parasitic rear side absorption loss, $2.17\ mA/cm^2$ escape loss and a parasitic absorption in the top cell layers of $0.26\ mA/cm^2$. The substantial rear side absorption loss can be explained by grating induced plasmons, caused by the corrugated metal in the real system. Comparing the grating performance with the flat reference, shown in FIG. 3, a current density gain of $1.1\ mA/cm^2$ is observed. A rear side structured with random pyramids shows minimal escape losses and provides a further improved light trapping with a current gain of $2.5\ \frac{mA}{cm^2}$ compared to the planar reference.

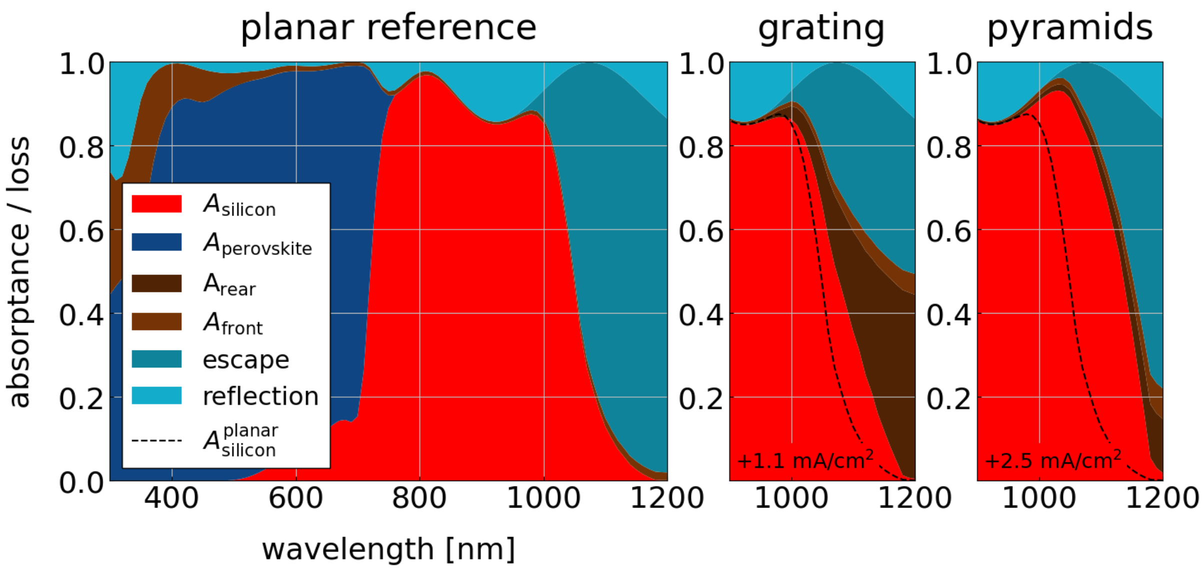

Figure 3. Comparison of simulated EQE for different rear side light trapping structures. A grating shows an improvement in comparison to a planar rear side but is outperformed by a standard random pyramid structure.

Two different approaches are available for further optimization of the light trapping in this system. On the one hand, it is reasonable to work on the passivation of p-TOPCon on random pyramids to benefit from their superior light trapping. On the other hand, the reduction of the massive parasitic absorption in the grating structure (comp. Fig. 3) is also an interesting option. Since we assume that the parasitic absorption is caused by plasmonic resonances at the structured metal surface, it would be good to planarize the grating and to build it out of dielectric materials (similar to the grating implementation in the simplified simulation described above). An interesting option would be to deposit a periodic structure consisting of amorphous silicon on the solar cell and to planarize it with photoresist. The solar cell would then be completed by a planar metal surface with local point contacts.

5. Optical influence of a tunnel junction

For the large-scale deployment of PV, the availability of resources will be a major challenge [8]. From this point of view, a silicon tunnel diode is a promising indium-free interconnection layer replacing the widely used ITO. Therefore, the optical model is used to evaluate the effect of a silicon tunnel diode in the presented context. To do so the ITO layer is removed from the stack and the poly silicon tunnel junction is assumed to have the same optical properties as the bulk material. With this approach free carrier absorption is disregarded.

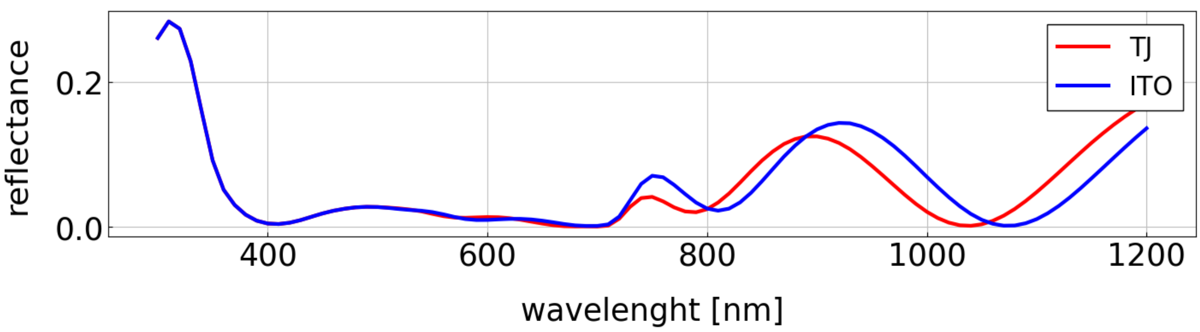

Figure 4. Reflection loss in a system with ITO recombination layer (TCO) compared to a device with a tunnel junction as interconnection.

FIG. 4 compares the reflection loss in a tandem solar cell with tunnel junction and with recombination ITO. A shift of the reflection spectra towards shorter wavelength is observed. This shift comes along with a slight decrease of reflection at wavelengths below 1070 nm and an increase for longer wavelengths. The overall performance of the systems is equivalent.

6. Conclusion

The investigated rear side grating structure leads to a current gain of $1.1\ mA/cm^2$. This is significantly lower than the light trapping provided by a standard random pyramid texture and cannot be compensated by the electrical benefits of a better passivation. The optical performance of the grating could be improved by reducing the parasitic absorption. This could be achieved by planarizing the grating and to build it out of dielectric materials. With such an improved architecture, the grating would be very promising. Further optimisation of the system includes either the improvement of p-TOPCon on textured surfaces or the minimisation of parasitic absorption in the rear side grating.

In addition, it could be shown that the integration of a poly silicon tunnel junction has no major influence on the optical performance of the tandem solar cell. On the other hand, it could provide an indium free recombination junction which promises a lean integration in current industrial process technology. Therefore, there is a great interest to integrate the tunnel junction into the presented system.

Data availability statement

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Author contributions

Mario Hanser: Conceptualization, Simulation, Investigation, Visualization, Roles/Writing – original draft. Oliver Höhn: Resources. Jan Benick: Resources. Benedikt Bläsi: Conceptualization, Resources, Writing – review & editing. Stefan Glunz: Funding acquisition, Supervision.

Competing interests

The authors declare no competing interests.

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References

1. P. Schygulla, R. Müller, D. Lackner, O. Höhn, H. Hauser, B. Bläsi, F. Predan, J. Benick, M. Hermle, S. W. Glunz, and F. Dimroth, “Two-terminal III–V//Si triple-junction solar cell with power conversion efficiency of 35.9 % at AM1.5g,” Prog Photovoltaics, pip.3503, 2021. DOI: https://doi.org/10.1002/pip.3503.
2. ITRPV, International Technology Roadmap for Photovoltaic (ITRPV): 2021 Results.

3. R. Cariou, J. Benick, F. Feldmann, O. Höhn, H. Hauser, P. Beutel, N. Razek, M. Wimplinger, B. Bläsi, D. Lackner, M. Hermle, G. Siefer, S. W. Glunz, A. W. Bett, and F. Dimroth, “III–V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration,” Nature Energy, vol. 3, no. 4, pp. 326–333, 2018. DOI: https://doi.org/10.1038/s41560-018-0125-0.

4. N. Tucher, J. Eisenlohr, P. Kiefel, O. Höhn, H. Hauser, I. M. Peters, C. Müller, J. C. Goldschmidt, and B. Bläsi, “3D optical simulation formalism OPTOS for textured silicon solar cells,” Opt. Express, vol. 23, no. 24, pp. A1720, 2015. DOI: https://doi.org/10.1364/OE.23.0A1720.

5. N. Tucher, O. Höhn, J. C. Goldschmidt, and B. Bläsi, “Optical modeling of structured silicon-based tandem solar cells and module stacks,” Optics Express, vol. 26, no. 18, A761, 2018. DOI: https://doi.org/10.1364/OE.26.00A761.

6. C. Messmer, B. S. Goraya, S. Nold, P. S. Schulze, V. Sittinger, J. Schön, J. C. Goldschmidt, M. Bivour, S. W. Glunz, and M. Hermle, “The race for the best silicon bottom cell: Efficiency and cost evaluation of perovskite–silicon tandem solar cells,” Progress in Photovoltaics: Research and Applications, 2020. DOI: https://doi.org/10.1002/pip.3372.

7. IEC 60904-3 (Ed. 4), 2019.

8. J. C. Goldschmidt, L. Wagner, R. Pietzcker, and L. Friedrich, “Technological learning for resource efficient terawatt scale photovoltaics,” Energy & Environmental Science, vol. 14, no. 10, pp. 5147–5160, 2021. DOI: https://doi.org/10.1039/D1EE02497C.