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Detailed 3D Optical Modelling of Interdigitated Back Contact Solar Cells

Miha Kikelj¹, Benjamin Lipovšek¹, Matevž Bokalič¹, Florian Buchholz² and Marko Topič¹

¹University of Ljubljana, Faculty of Electrical Engineering, Tržaška cesta 25, SI-1000 Ljubljana, Slovenia

²International Solar Energy Research Center Konstanz e.V., Rudolf-Diesel-Straße, D-78467 Konstanz, Germany

Abstract—A development and calibration of a detailed 3D coupled ray-wave optical model for accurate simulations of laterally varying photovoltaic structures is presented and applied for the analysis of interdigitated back contact cells. Four key aspects, which predominantly contribute to the accuracy of optical simulations are highlighted through the validation of the model. The applicability of the model is demonstrated through an example of electroluminescence simulations.

Keywords—Solar cells, Interdigitated back contact, Optical Modelling, Electroluminescence, TCAD Sentaurus

I. INTRODUCTION

In the everlasting chase for more and more efficient solar cells and modules, new and commercially not yet widespread technologies are coming into play [1]. A transition to highly efficient interdigitated back contact solar cells (IBC SCs) and their integration within new, cut-cell module concepts could be a relatively simple, cost effective solution which will drive further expansion of photovoltaics (PV) as one of the key renewable energy sources.

In terms of numerical modelling, IBC SCs provide a new challenge that requires a shift to full-3D modelling environment. Due to highly dynamic vertical and especially lateral variations of materials and surface structures, a conventional layer stack model [2] is no longer sufficient for description of the complex optical and electrical situation in these devices. Capturing the lateral dynamics of interchanging p+ and n+ regions, as shown

in Fig. 1, calls for a detailed 3D model, which is able to accurately model the electro-optical phenomena within a characteristic period of the cell.

Development and validation of a detailed optical model of such proportions, based on a synergy and evolution of previous optical models [3], [4], is key to any further numerical simulations and provides a starting point for numerically supported analysis and optimization of complex PV structures. First, the model provides an insight into the optical situation of the device itself and is crucial for the optimization of the cell's structure to increase light trapping and minimize optical losses. Furthermore, any electrical analysis of the device under illumination calls for accurate calculation of spatially resolved optical generation as an input parameter. The accuracy of the optical model therefore directly influences the final accuracy of electrical simulations, e.g. at the maximum power point (MPP). Last but not least, an accurate optical model is key to correct interpretation of measurement results of spatially resolved methods, which combine the optical and the electrical phenomena [5] such as electroluminescence (EL) and light beam induced current (LBIC). The failure to establish a detailed optical model could lead to wrongly interpreted or even unnoticed underlying electrical phenomena, which would be masked by a laterally dynamic optical situation of complex PV structures. In our contribution, we therefore present and validate a 3D optical model, which can accurately and consistently capture the optical situation of complex PV structures, in particular IBC SCs.

Fig. 1. a) Cross-section (top) and electroluminescence closeup of the Zebra IBC cell at 1.0 I_{sc_STC} , b) electroluminescence line scans at different injection levels.

Fig. 2. a) RTA of the Zebra IBC cell illuminated from the front side – initial model, b) RT of the cell illuminated from the back side – initial model, c) RTA of the cell illuminated from the front side – upgraded model, and d) RT of the cell illuminated from the back side – upgraded model

II. MODEL DEVELOPMENT AND EXPERIMENTAL VALIDATION

In this work, we developed and validated a full 3D optical model on the basis of the Zebra IBC cell [6], [7]. We started off with a detailed 3D geometrical representation of the device's structure (Fig. 1.a) in Sentaurus TCAD [8], carefully recreating each individual layer, the random pyramids and other major geometrical features of the cell layers and interfaces.

Light propagation through the device was modelled with the coupled modelling approach (CMA) [9], with raytracing as the main method, while the thin layers of the antireflective coating (ARC) were modelled using the transfer matrix method (TMM). Realistic optical constants [2], [10] of the materials were taken as the input parameters. The model also includes the effect of free-carrier absorption (FCA) [11], [12], which was estimated from the measured doping profiles. For the purpose of detailed optical modelling we developed a custom boundary condition, using the Physical Model Interface (PMI) provided by Sentaurus TCAD in order to combine the effects of the thin-layer ARC, ray scattering and FCA on a single boundary.

Using the initial implementation of the model, we were able to obtain reflection, transmission, and absorption (RTA) trends,

as shown in Fig. 2.a and 2.b. While relatively good agreement with the measurement of the physical device can be observed, the results revealed several key aspects of the model, which needed to be improved for viable reproduction of the measurements especially in the IR wavelength region. We attributed the main differences to four key properties: the exact thicknesses of the thin layers of the ARC (mismatch in the UV region and the position of the interference at the back side), the reflectivity of the metal contact fingers at the back side of the cell (offset of the reflectivity at the back side), light scattering at the back side of the cell (underestimated light trapping in the bulk), and the non-ideality of the random pyramid texture. We then calibrated each of the key aspects one by one in a systematic manner, until a satisfactory match between the simulations and the measurements was achieved (Fig. 2.c and 2.d).

A. ARC Layer Thicknesses

The first and perhaps the easiest aspect of the model calibration was the ARC. Even though we knew the layer thicknesses of the SiN_x and the SiO_2 of the manufactured samples, some calibration was still required for the model to better represent the measurements. We calibrated the ARC layer thicknesses for the ARC at the front, and separately for the layers

in the p⁺ and n⁺ regions at the back. We varied the thicknesses of the individual layers until an optimal R² value was achieved, which resulted in a better match especially for the interference peak and valley in Fig. 2.d.

B. Reflectivity of the Screen-printed Metal Fingers

After calibrating the thin-film ARC layers we observed that the simulation of reflectance at the back side of the cell was still overestimated in comparison with the measured reflectance (Fig 2.b). Because of the shift throughout most of the wavelength range, we attributed the difference to the reflectivity of the screen-printed metallization contact fingers. Further experiments have shown that the reflectance computed from the wavelength dependent refractive index greatly overestimates (30%) the measured reflectance in the region above 350 nm, as shown in Fig. 3, which is probably caused by the roughness of the screen-printed fingers' surface. By considering the actual measured metallization reflectance in the simulations, we eliminated the offset and vastly improved the agreement with the measurements (Fig. 2.d).

Fig 3. Comparison between the measured and the simulated reflectance at the air-finger interface.

C. Scattering at the Flat Interface

In realistic devices the rear, untextured surface is not ideally flat, as confirmed by laser scanning microscopy (LSM) images of the sample cells. In order to improve light trapping in the device, increase the *EQE*, and improve the matching between measured and simulated *R* and *T* in the region above 1000 nm, we introduced light scattering at the rear surface of the cell. We implemented a custom Monte-Carlo scattering model, which combines the specular and the diffuse (Lambertian) reflection and transmission. We calibrated the model until a satisfactory match between the measurements and the simulation was achieved. Even though increased scattering at the rear “flat” interface does improve the matching between the measurements and the simulation an adequate fit, using only the scattering model at the rear surface, would require an unrealistic specular-to-diffuse ratio.

D. Realistic Micro-Pyramid Texture

It turned out that in order to fully capture the optical situation in the device and improve the matching to the measurements in the long wavelength region and with respect to the ratio between the total and diffusely reflected light, we had to pay close attention to the random micro-pyramid texture at the front side of the cell. Up until this point the generated texture used in simulations was random in nature, but only with respect to the peak height and the peak position of the micro-pyramids, while the base angle of the pyramids was kept at the value of the ideal base angle of approximately 54°. Following the studies in [13] and an analysis of the LSM measurements of the textured surface measured in-house, we improved the generated micro-pyramid texture by incorporating a normal distribution of base angles, centered around a slightly lower base angle of approximately 52°. This modification also further decreased the reflection an increased transmission in the region above 1000 nm.

Having accounted for and calibrated these four key aspects, we were able to significantly improve the accuracy of the simulations, which can be observed as a vast improvement over the initial model, bringing the simulated RTA results much closer to the experiment in the entire wavelength range, as shown in Fig. 2.c and 2.d. An additional aspect, which could further improve the simulation results, would be the calibration of the FCA model, which was not possible with the samples we had at hand.

III. APPLICATION OF THE MODEL

Besides enabling accurate simulation of reflection, transmission and absorption for further use in electrical modelling, the calibrated, geometrically correct 3D optical model of the physical device developed in the scope of this work proves a powerful tool in recreating the results of spatially resolved measurement methods (EL, LBIC) with simulations. This important link between experimental and numerical work can vastly improve the interpretation of measured data which leads to better understanding of the underlying physical phenomena and paves the road for further device optimization.

Fig 4. Measured and simulated EL profile using the developed model, given that the light is generated homogeneously throughout the device.

As an example, we simulated an EL profile of the Zebra IBC cell under injection as it would be seen with the camera experimentally (Fig. 1) in order to better understand the underlying electrical phenomena. Both the measured and the simulated EL profiles obtained by the calibrated optical model of the Zebra IBC are shown in Fig. 4. Although the results could be further improved by increasing the number of rays in the simulation and therefore reducing the noise in the resulting EL profile, it nevertheless demonstrates the applicability of the model in the interpretation of measurements.

IV. CONCLUSION

In this contribution, we developed and validated a complex 3D optical model utilizing a coupled optical modelling approach, which can accurately model the optical situation in complex laterally varying structures (such as IBC SCs) with unprecedented detail. We identified the thin-film layer thicknesses, the reflectivity of the Ag screen-printed contact fingers, the roughness of the interfaces, and the ideality of micro-pyramids as four key factors contributing to the high accuracy of the model. With the ability to avoid the pitfall of erroneous result interpretation due to dominant optical phenomena, the model proves a valuable and essential tool in further research and optimization of laterally varying highly efficient photovoltaic devices.

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REFERENCES

- [1] 'International Technology Roadmap for Photovoltaics (ITRPV)'. Apr. 2020.
- [2] J. Krc and M. Topic, *Optical Modeling and Simulation of Thin-Film Photovoltaic Devices*. CRC Press, 2013.
- [3] B. Lipovšek, J. Krč, and M. Topič, 'Optical Model for Thin-Film Photovoltaic Devices with Large Surface Textures at the Front Side', *Informacije MIDE M - Journal of Microelectronics, Electronic Components and Materials*, vol. 41, no. 4, p. 8, 2011.
- [4] M. Topič, M. Sever, B. Lipovšek, A. Čampa, and J. Krč, 'Approaches and challenges in optical modelling and simulation of thin-film solar cells', *Solar Energy Materials and Solar Cells*, vol. 135, pp. 57–66, Apr. 2015, doi: 10.1016/j.solmat.2014.09.026.
- [5] M. Padilla *et al.*, 'Surface recombination parameters of interdigitated-back-contact silicon solar cells obtained by modeling luminescence images', *Solar Energy Materials and Solar Cells*, vol. 120, pp. 363–375, Jan. 2014, doi: 10.1016/j.solmat.2013.05.050.
- [6] J. Libal *et al.*, 'The Zebra Cell Concept - Large Area n-Type Interdigitated Back Contact Solar Cells and One-Cell Modules Fabricated Using Standard Industrial Processing Equipment', in *27th European Photovoltaic Solar Energy Conference and Exhibition*, Oct. 2012, pp. 567–570. doi: 10.4229/27thEUPVSEC2012-2AO.2.1.
- [7] R. Kopecek *et al.*, 'ZEBRA technology: low cost bifacial IBC solar cells in mass production with efficiency exceeding 23.5%', in *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, Jun. 2020, pp. 1008–1012. doi: 10.1109/PVSC45281.2020.9300503.
- [8] 'Sentaurus Device'. <https://www.synopsys.com/silicon/tcad/device-simulation/sentaurus-device.html> (accessed May 14, 2020).
- [9] Z. Lokar *et al.*, 'Coupled modelling approach for optimization of bifacial silicon heterojunction solar cells with multi-scale interface textures', *Opt. Express, OE*, vol. 27, no. 20, pp. A1554–A1568, Sep. 2019, doi: 10.1364/OE.27.0A1554.
- [10] A. Fell *et al.*, 'Input Parameters for the Simulation of Silicon Solar Cells in 2014', *IEEE Journal of Photovoltaics*, vol. 5, no. 4, pp. 1250–1263, Jul. 2015, doi: 10.1109/JPHOTOV.2015.2430016.
- [11] S. C. Baker-Finch, K. R. McIntosh, D. Yan, K. C. Fong, and T. C. Kho, 'Near-infrared free carrier absorption in heavily doped silicon', *Journal of Applied Physics*, vol. 116, no. 6, p. 063106, Aug. 2014, doi: 10.1063/1.4893176.
- [12] M. Nedeljkovic, R. Soref, and G. Z. Mashanovich, 'Free-Carrier Electrefraction and Electroabsorption Modulation Predictions for Silicon Over the 1–14- um Infrared Wavelength Range', *IEEE Photonics Journal*, vol. 3, no. 6, pp. 1171–1180, Dec. 2011, doi: 10.1109/JPHOT.2011.2171930.
- [13] H. Mäkel, H. Holst, M. Löhmann, E. Wefringhaus, and P. P. Altermatt, 'Detailed Analysis of Random Pyramid Surfaces With Ray Tracing and Image Processing', *IEEE Journal of Photovoltaics*, vol. 6, no. 6, pp. 1456–1465, Nov. 2016, doi: 10.1109/JPHOTOV.2016.2601947.