LIGHT-TRAPPING AND ELECTRICAL TRANSPORT IN RANDOMLY ROUGH THIN-FILM SOLAR CELLS

Piotr Kowalczewski, Angelo Bozzola, Marco Liscidini, and Lucio C. Andreani
Department of Physics, University of Pavia
Via Bassi 6, I-27100 Pavia, Italy

ABSTRACT: In this work, we use a rigorous electro-optical model to study silicon solar cells with random textures. First, we calculate the efficiency limits of silicon solar cells by considering a *p*-*n* junction and solving the drift-diffusion equations as a function of the cell thickness, assuming the Lambertian light trapping. Second, we aim to design realistic solar cells to get as close as possible to the efficiency limits. We use an efficient numerical model, which allows us to study a wide range of the absorber thickness and material parameters. We theoretically demonstrate how to simultaneously increase short-circuit current and improve open-circuit voltage by, respectively, texturing the front surface and decreasing the absorber thickness.
Keywords: light-trapping, thin films, roughness, electrical properties, modelling

1 INTRODUCTION

Two questions are central for silicon photovoltaics:

1. **What are the efficiency limits of silicon solar cells?**
2. **How to design solar cells to get as close as possible to the limits?**

In the first part of this work we try to estimate the efficiency limits of silicon solar cells. The limits reported in the literature [1-3] are calculated using the diode equation and assuming the ”narrow-base” approximation (i.e., quasi-Fermi levels are assumed to be constant within the base). Instead, we calculate the efficiency limits by explicitly considering a *p*-*n* junction: we numerically solve the drift-diffusion equations as a function of the cell thickness, assuming the Lambertian light trapping. To solve the drift-diffusion equations, we use Finite-Element Method implemented in the Silvaco Atlas device simulator [4].

In the second part of this contribution, we aim to design realistic solar cells to get as close as possible to the efficiency limits. In particular, we study silicon solar cells with random textures. Our numerical framework consists of two parts: (1) the optical calculations performed using Rigorous Coupled-Wave Analysis (RCWA) [5]; (2) the electrical calculations, performed using the Atlas simulator. Both parts are combined together, so that the output from the optical calculations is used as an input for the electrical model. This approach proves to be numerically efficient, which allows us to study a wide range of the absorber thickness and material parameters.

The main difference between the calculations in the first and second part of this paper is the optical input used for the device simulator. In the first part, when calculating the efficiency limits, we use the Lambertian photogeneration rate calculated analytically. In the second part, we consider a complete rough topography, and we numerically calculate the corresponding photogeneration rate.

2 EFFICIENCY LIMITS – HOW FAR WE CAN GET?

Let us first consider a theoretical structure sketched in Fig. 1. The structure consists of a 5 nm thick *n*-type

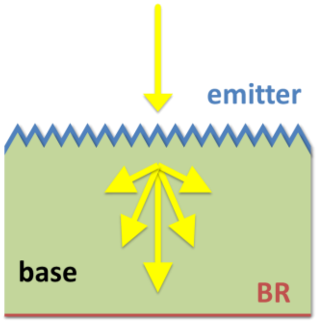


Figure 1: Theoretical structure used to calculate the efficiency limits of silicon solar cells. The *n*-type emitter (blue region) is 5 nm thick. All the incident light is isotropically scattered, i.e., the photogeneration rate corresponds to the Lambertian limit. Finally, at the rear interface we assume a perfect back reflector (BR).

emitter (blue region), with the doping concentration equal to 3.16×10^{18} cm^{-3} (the doping concentration in the emitter has been optimized to achieve the highest efficiency). Moreover, such a thin emitter minimizes the recombination losses in this layer. Throughout the calculations we do not change the emitter thickness, and therefore also the optimal doping stays the same.

We assume the photogeneration rate corresponding to the Lambertian limit, meaning that all the incident light is isotropically scattered [6]. Finally, in the calculations we consider two intrinsic loss mechanisms: Auger and radiative recombination.

In Fig. 2 we show the efficiency limits of silicon solar cells as a function of the absorber thickness. First, for the comparison, we calculate the efficiency limit using the diode equation, according to the formalism derived in Ref. [1]. Then, we calculate the limit by numerically solving the drift-diffusion equations. Here, we distinguish two cases: (1) optimized doping, which means that for each thickness we have optimized the base doping; (2) constant doping, which means that we assumed the base doping equal to 3.16×10^{16} cm^{-3} for the whole thickness range.

One can see a difference of the order of 1-2% (absolute units) between the limit calculated with the diode equation and that calculated with the device simulator. The difference is largest for thinner cells. This is partly due to band-gap narrowing (BGN), which has been included in the numerical simulations, but has been

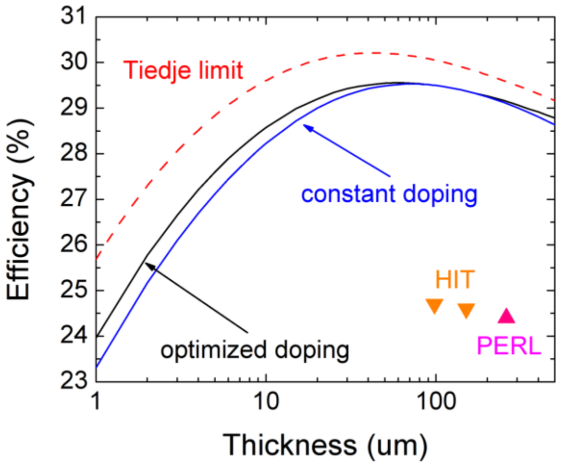


Figure 2: The efficiency limits of silicon solar cells as a function of the absorber thickness. Dashed line: the limit calculated using the diode equation, according to the formalism derived in Ref. [1]. Solid lines: the limit calculated by solving the drift-diffusion equations and assuming the Lambertian photogeneration rate. Optimized doping means that for each thickness we have optimized the base doping. For the constant doping, we assumed the base doping equal to 3.16×10^{16} cm^{-3} for the whole thickness range. These results are compared with the efficiencies of the HIT and PERL cell.

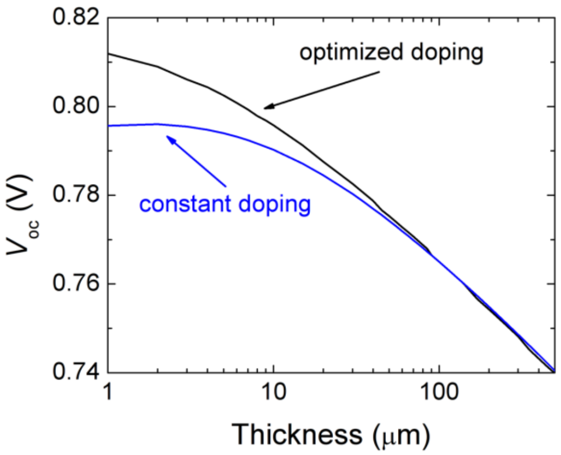


Figure 3: Open-circuit voltage as a function of the absorber thickness. These results correspond to the calculations of efficiency shown in Fig. 2.

neglected in the calculations performed using the diode equation.

Optimizing the base doping allows one to improve the maximum efficiency by around 0.5% (absolute units). The optimal base doping is highest for thinner cells (reaching 3.16×10^{17} cm^{-3}) and decreases with the increasing thickness.

Overall, the efficiency as a function of the absorber thickness shows a wide maximum, and small changes in the input parameters may quite radically change the optimal thickness.

These results are compared with the efficiencies of the state-of-the-art HIT and PERL cell [7,8], showing the gap (or the room for improvement) of the order of 4-5% (absolute units).

The trends of the photocurrent corresponding to the Lambertian limit as a function of the absorber thickness are well discussed in the literature [9]. Yet, we find the trends of open-circuit voltage V_{oc} particularly interesting. In Fig. 3 we show V_{oc} as a function of thickness. These results correspond to the calculations of efficiency shown in Fig. 2. Once again we consider two cases: optimized and constant doping.

It can be seen that optimizing the base doping allows one to improve V_{oc}. Moreover, thin cells generally benefit from higher V_{oc}, yet it tends to saturate with the decreasing absorber thickness. We believe this is due to BGN, as V_{oc} is related to energy band-gap.

Let us now consider an extrinsic loss mechanism, namely surface recombination. With such a thin emitter, the performance of the cells is likely to be limited by recombination at the rear (silicon/back reflector) interface [10]. In Fig. 4 we show the limiting efficiency of silicon solar cells in the presence of the rear surface recombination. One can observe a significant drop of the limiting efficiency with increasing surface recombination velocity (SRV). These results confirm the necessity of an excellent surface passivation at the rear interface.

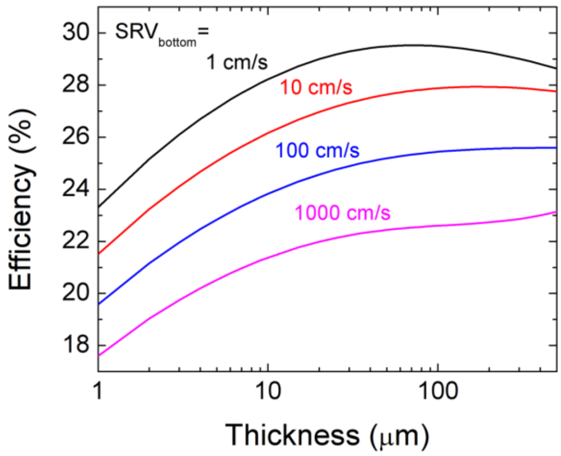
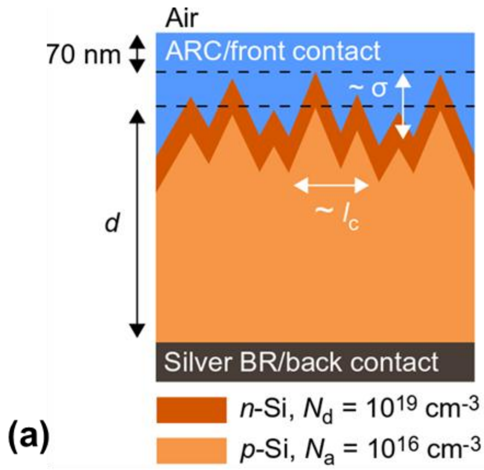


Figure 4: The limiting efficiency of silicon solar cells in the presence of surface recombination at the rear (silicon/back reflector) interface. Different curves correspond to different values of surface recombination velocity (SRV).

3 LIGHT TRAPPING AND TRANSPORT LOSSES

Let us now consider solar cell structures with realistic random textures, sketched in Fig. 5(a). The roughness has the optimal parameters for c-Si: σ = 300 nm, l_c = 160 nm, which allows one to achieve around 94% of the photocurrent corresponding to the Lambertian limit [11,12]. The junction consists of an 80 nm thick *n*-type emitter and a *p*-type base with thickness *d*. We take a 70 nm thick anti-reflection coating (ARC) with refractive index *n*=1.65. The ARC also serves as a front contact (i.e., the carriers are collected at the ARC/silicon interface), whereas a silver back reflector serves as a back contact.

In Fig. 5(b) we show an example photogeneration rate calculated using RCWA for the 10 μm thick solar cell structure. The main plot shows the photogeneration rate close to the texture, whereas the inset shows the whole cell.



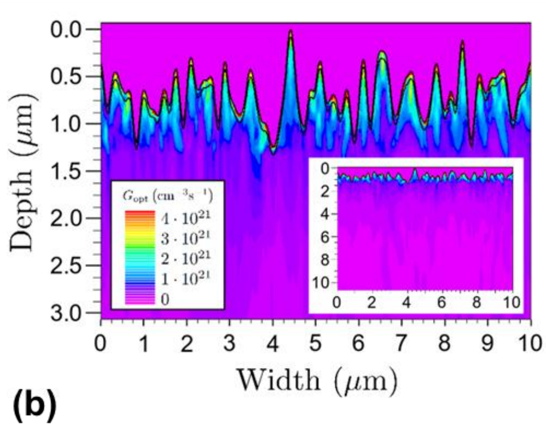


Figure 5: (a) Silicon solar cell structure with random texture considered in the electro-optical simulations. (b) Photogeneration rate calculated using RCWA for the 10 µm thick solar cell structure. The main plot shows the photogeneration rate close to the texture, whereas the inset shows the whole cell.

The photogeneration rate calculated using RCWA is taken as an input for the Silvaco Atlas device simulator. The drift-diffusion equations are solved by means of Finite-Element Method. Moreover, we include Shockley-Read-Hall (SRH) recombination, which results from material imperfections. We assume that the diffusion length of minority carriers in the base corresponds to the state-of-the-art thin-film c-Si solar cell [13]: L_n = 232 µm. The details of our numerical approach can be found in Ref. [10]. At this point we do not consider losses related to surface recombination.

In Fig. 6 we show efficiency as a function of the absorber thickness, calculated for the flat and textured solar cells. The dashed lines refer to the structures limited by Auger recombination, whereas the solid lines refer to the structures with additional SRH recombination. The triangles denote the efficiencies of the HIT cell (green) and Petermann cell (blue).

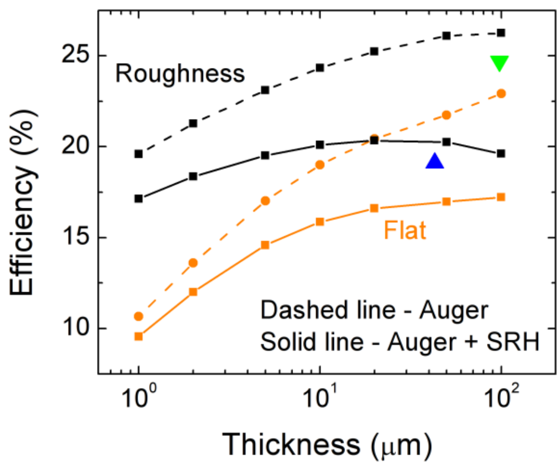


Figure 6: Efficiency as a function of the absorber thickness, calculated for the flat and textured solar cells. The dashed lines refer to the structures limited by Auger recombination, whereas the solid lines refer to the structures with additional SRH recombination. The triangles denote the efficiencies of the HIT cell (green) and Petermann cell (blue).

First of all, the textured cells exhibit significantly higher efficiencies, comparing to the flat cells. This is because of the photocurrent enhancement due to surface texturing. As expected, the improvement is particularly substantial for thinner cells.

Moreover, when SRH recombination is considered, one can clearly observe a maximum for the textured cells. The optimal thickness results from an interplay between current and voltage (i.e., light trapping and the electrical transport losses). For the assumed material quality, the optimal thickness is around 20-40 µm. When only Auger recombination is considered, the optimal thickness shifts towards thicker cells (100 µm and more).

Finally, the efficiency measured for the Petermann cell is close to our calculations for the cells limited by SRH recombination. Similarly, efficiency measured for the HIT cell is close to our calculations for the cells limited by Auger recombination. This would suggest that the HIT cell is characterized by a much higher material quality.

4 SURFACE RECOMBINATION

At this point we have demonstrated that texturing the front surface gives an excellent photocurrent enhancement, and thus results in a significant increase of efficiency. These results have been obtained assuming a perfect surface passivation. Yet, the direct consequence of texturing the surface is an increased surface area, which in turn may increase surface recombination. Therefore, it is justified to ask whether the efficiency enhancement due to texturing persists also in the presence of surface recombination.

In Fig. 7 we plot efficiency as a function of top and bottom SRV for the 10 µm thick textured c-Si solar cell. It can be shown that efficiency is limited by recombination at the silicon/back reflector interface; front surface recombination velocity (SRV) as high as 10^3 cm/s does not impact the cell performance. An intuitive explanation may be as follows: only minority carriers are

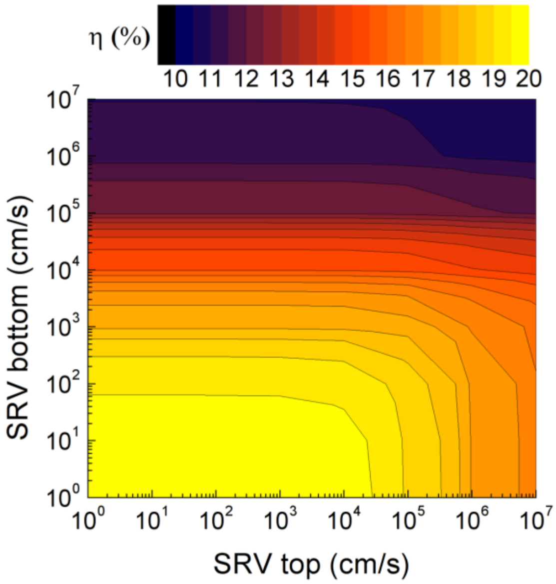


Figure 7: Efficiency as a function of top and bottom SRV for the 10 µm thick textured c-Si solar cell. SRH recombination is included.

sensitive to bulk and surface recombination losses. In our design, the junction is shallow (80 nm), and thus minority carriers are mostly in the much thicker base. Therefore, one can engineer the front surface to a large extent without compromising on efficiency [10]. Moreover, these results confirm the conclusions drawn in Sec. 2, namely that the cell performance is strongly limited by surface recombination at the rear interface.

5 CONCLUSIONS

In the first part of this contribution, we have calculated the efficiency limit of silicon solar cells as a function of the absorber thickness. To do so, we have numerically solved the drift-diffusion equations, assuming the Lambertian photogeneration rate. The maximum efficiency calculated in this way is 29.6%. In the second part of this work, we have performed complete electro-optical simulations of silicon solar cells with random textures. In this case, the maximum efficiency was 26.3% (assuming only intrinsic Auger recombination).

In our calculations we have consider the absorber thickness ranging from 1 to 100 µm. We have demonstrated that thinner solar cells can be more efficient than thicker ones – the optimal thickness results from an interplay between the electrical transport and light-trapping strategy.

Moreover, we have shown that one can engineer the front surface to a large extent without compromising on efficiency, as long as the emitter is thin enough. Yet, the cell performance is strongly limited by recombination at the rear (silicon/back reflector) interface, which highlights the necessity of an excellent surface passivation.

Finally, we have theoretically demonstrated that it is possible to simultaneously (1) improve the photocurrent due to surface texturing, (2) improve open-circuit voltage by reducing the absorber thickness.

6 ACKNOWLEDGMENTS

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