Solar Energy Materials & Solar Cells 143 (2015) 260–268

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Towards the efficiency limits of silicon solar cells: How thin is too thin?

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ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form
17 June 2015
Accepted 29 June 2015

Keywords:
Silicon solar cells
Efficiency limits
Device modelling
Auger recombination
Surface recombination
Light trapping

ABSTRACT

It is currently possible to fabricate crystalline silicon solar cells with the absorber thickness ranging from a few hundreds of micrometres (conventional wafer-based cells) to devices as thin as 1 µm. In this work, we use a model single-junction solar cell to calculate the limits of energy conversion efficiency and estimate the optimal absorber thickness. We have found that the limiting efficiency for cells in the thickness range between 40 and 500 µm is very similar and close to 29%. In this regard, we argue that decreasing the thickness below around 40 µm is counter-productive, as it significantly reduces the maximum achievable efficiency, even when an optimal light trapping is implemented. We analyse the roles of incomplete light trapping and extrinsic (bulk and surface) recombination mechanisms. For a reasonably high material quality, consistent with present-day fabrication techniques, the optimal thickness is always higher than a few tens of micrometres. We identify incomplete light trapping and parasitic losses as a major roadblock for improving the efficiency upon the current record of 25.6% for silicon solar cells. Finally, considering the main parameters that impact the solar cell performance, we quantify the requirements for achieving a given efficiency, which helps us to establish a proper design strategy for high efficiency silicon solar cells.

1. Introduction

In this work we focus on the efficiency limits of crystalline silicon (c-Si) solar cells. In this regard, we consider both ideal devices (perfect material and interfaces), as well as more realistic conditions, including defect-related recombinations, parasitic losses, and non-optimal light management. It is currently possible to fabricate c-Si solar cells with absorber thickness values that differ by two orders of magnitude. On the one end of the thickness range, there are conventional wafer-based c-Si solar cells with the absorber thickness of the order of a few hundreds of micrometres [1]. Epitaxial growth allows fabricating solar cells with the thickness of a few tens of micrometres [2]. Finally, epitaxy-free fabrication [3,4] makes possible fabricating c-Si solar cells with the absorbing layer as thin as 1 µm. For a proper design strategy, it is important to determine the optimal absorber thickness in terms of the energy conversion efficiency. We address this question using a model single-junction silicon solar cell.

It is well known that reducing the silicon thickness leads to the reduction of the total absorption, and thus of the photocurrent. This has to be compensated by implementing an appropriate light-trapping scheme. Yet, it should be emphasized that even when an optimal light trapping is applied (i.e., perfect anti-reflection action combined with a Lambertian scatterer), the maximum achievable absorption still decreases with decreasing material thickness [5,6]. On the other hand, V_{oc} generally tends to decrease with increasing thickness. For a given material quality, this leads to an optimal thickness that maximizes the conversion efficiency [6,7]. In this context, the goal of this work is twofold: First, to establish the most suitable thickness range for c-Si solar cells to approach the efficiency limits. Second, to identify the parameters that have to be improved in order to increase the energy conversion efficiency above the current record of 25.6% [8].

We use efficiency as a figure of merit to assess different solar cell structures. This is motivated by the fact that the cost of electricity is mainly determined by the efficiency, rather than by the cost of the active material (which, in the case of silicon, is constantly decreasing): cost of the active material is only a part of the cost of a photovoltaic module. This, in turn, is only a part of the total cost of a photovoltaic system. On the other hand, increasing the efficiency improves the performance of the whole system. In this regard, it is particularly important to estimate the optimal absorber thickness range that maximizes the efficiency. In our analysis we include intrinsic Auger recombination, as well as defect-based bulk and surface recombination mechanisms. We also introduce a simple approach that allows us to consider parasitic losses. We compare our results with the measured

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http://dx.doi.org/10.1016/j.solmat.2015.06.054
0927-0248/

performance of state-of-the-art silicon solar cells, showing the room for improvement in terms of current, voltage, and fill factor. We pay particular attention to parasitic losses, which we believe are the major roadblock in reaching efficiency above the current record of 25.6% [8].

A review of the efficiency limits of silicon solar cells is given in Ref. [9]. The limits reported in the literature [10–12] are usually calculated using the idealized diode equation [13]. This approach has the following limitations:

1. The diode equation gives less accurate results when the cell thickness is decreasing. We attribute this inaccuracy to the assumptions underlying the treatment of the space-charge region (SCR) in the idealized diode formalism. We further discuss the accuracy of the results obtained using the idealized diode equation in the Appendix.
2. Solar cells require selective contacts, which can be achieved using a p–n junction. Yet, the junction is not explicitly considered in the ideal diode approach. Therefore, the ideal diode equation gives unrealistic results that overestimate efficiency for undoped silicon.

Our approach allows us to overcome these limitations: we analytically obtain the photogeneration rate (ranging from double-pass absorption to Lambertian light trapping), explicitly consider a p–n junction, and numerically solve the drift–diffusion equations. This allows us to calculate more realistic efficiency limits of silicon solar cells in a wide range of cell thicknesses and doping levels.

The paper is organized as follows: in Section 2 we describe our approach, based on an analytical photogeneration rate and numerical solution of the drift–diffusion equations. In Section 3 we calculate the efficiency limits of c-Si solar cells. In Section 4 we discuss the effects of incomplete light trapping. In Section 5 we cover the impact of bulk material imperfections on the cell performance, and we introduce a simple approach to include parasitic losses in the analysis. In Section 6 we discuss the role of surface recombination. In Section 7 we quantify the requirements, in terms of bulk and surface material quality, to achieve a given efficiency. Conclusions are given in Section 8. Finally, in the Appendix we compare the results of our numerical treatment with those obtained using the idealized diode equation.

2. Numerical approach

Let us consider the structure sketched in Fig. 1. It consists of a 5 nm thick n-type emitter and a p-type base of variable thickness. Such a thin emitter minimizes recombination losses in this heavily doped layer. To calculate the efficiency limits we assume no reflection at the front interface, a perfect back reflector (BR), and a Lambertian light trapping [14,15]. In Fig. 1 we schematically show the Lambertian scatterer at the front, yet we note that the structure considered in the calculations is one-dimensional, and the photogeneration rate as a function of depth is calculated analytically. Finally, we assume full-area contacts: the carriers are collected at the silicon/BR and emitter/transparent front contact interfaces. With these simplifying assumptions, we will be able to draw general conclusions, not related to a particular solar cell structure.

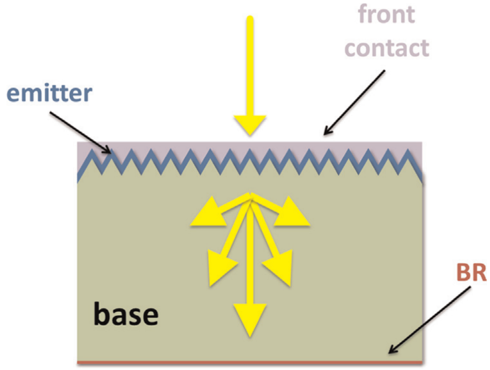

Fig. 1. Investigated solar cell structure consisting of a 5 nm thick n-type emitter (the blue region), p-type base (the green region), and a perfect back reflector (BR), which also serves as a back contact. The front surface is textured so that the incident light is scattered and trapped within the absorber. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

The photogeneration rate corresponding to the Lambertian limit is calculated as a function of energy and depth, according to Ref. [6]:

$$G_{\mathrm{LL}}(z,E)=\frac{\alpha_{\mathrm{lt}}\left(R_{\mathrm{b}}e^{-2\alpha_{\mathrm{lt}}w}e^{\alpha_{\mathrm{lt}}z}+e^{-\alpha_{\mathrm{lt}}z}\right)}{1-e^{-2\alpha_{\mathrm{lt}}w}\left(1-\dfrac{1}{n_{\mathrm{Si}}^{2}}\right)}\times\phi_{\mathrm{AM1.5G}},\qquad(1)$$

where n_{Si} is the refractive index of c-Si [16] and $\phi_{\mathrm{AM1.5G}}$ is the photon flux density corresponding to the AM1.5G solar spectrum [17]. The effective absorption coefficient α_{lt} is related to the light path enhancement in textured cells according to Ref. [15]. In the literature we can find a number of different strategies that allow approaching the Lambertian limit, including ordered [5,18–20] and quasi-ordered [21–23] photonic structures, as well as random textures [24–27].

The photogeneration rate calculated using Eq. (1) is integrated with respect to energy (over the solar spectrum) and used as the generation term in the drift–diffusion equations, which are solved using Finite-Element Method (FEM). We use FEM implemented in the commercial device simulator Silvaco Atlas [28]. This methodology is similar to the one described in our previous works [7,29].

3. Efficiency limits

We start by considering solar cells limited by intrinsic Auger recombination. We treat Auger recombination using the parametrization reported by Richter et al. [30]. In our calculations we assume that front and back surface recombination velocities are equal to 1 cm/s, unless specified otherwise. We also consider band gap narrowing (BGN) according to the model by Schenk [31]. Finally, we neglect free carrier absorption, which is a second-order effect [10,12]. Silicon is an indirect band gap material, and thus we also neglect losses related to radiative recombination, which may give an appreciable effect only for very thick cells. Yet, for the thick cells the probability of photon recycling increases [11], i.e., radiatively emitted photons are reabsorbed. These two effects are likely to compensate each other. In the Appendix we show that radiative recombination together with photon recycling have a negligible effect on the cell performance.

In Fig. 2(a) we show the limiting efficiency of c-Si solar cells as a function of the absorber thickness, calculated for the structure sketched in Fig. 1. For each thickness, we have simultaneously optimized the emitter and base doping (the doping profile in each layer is assumed to be constant). The efficiency as a function of emitter doping N_{d} has a wide maximum, and the optimal value $N_{\mathrm{d}}=1.5\times10^{18}\ \mathrm{cm}^{-3}$ does not change with the absorber thickness,