Journal of Physics: Conference Series **647** (2015) 012047 doi:10.1088/1742-6596/647/1/012047

Evaluation of the Collection Length and Optical Path Enhancement in a-Si:H Solar Cells

M. Fortes, E. Comesaña, J. A. Rodríguez, P. Otero, A. J. Garcia-Loureiro

Centro de Investigación en Tecnoloxías da Información da Universidade de Santiago de Compostela, CiTIUS. Santiago de Compostela, Spain

E-mail: `montserrat.fortes@usc.es`

Abstract. The characterization of the electrical parameters of solar cells is fundamental to improve their performance. In the case of a-Si:H thin film solar cells, the degrading effect of light has to be mitigated, among others, with thin absorber layers and light confinement techniques. The novelty of this paper is the development of method that evaluates both, the light trapping enhancement and the collection length of the carriers in these and other field-driven devices. In this research we compared experimental results of a-Si:H cells with our simulation model, obtaining good agreement.

1. Introduction

Thin film hydrogenated amorphous silicon (a-Si:H) solar cells have small ambipolar diffusion lengths (L_d). For undoped a-Si:H this value is 0.1-0.4 μm [1]. Therefore these cells use drift, rather than diffusion, as dominant transport mechanism. In the other hand, a-Si:H presents a light-induced degradation (LID) during the first hours of illumination. This phenomenon is known as Staebler-Wronski effect (SWE) and its impact is inversely proportional to the thickness of the i-layer [2]. Since thin i-layers are preferred, light confinement is imperative to increment the path of light and thus improve the absorbance of the cell. In the present article we disclose a method to evaluate the electric and optic performance of textured a-Si:H cells. We extract from the internal quantum efficiency parameters as important as the collection length and the optical enhancement factor.

2. Experimental sample

The 1 cm^2 thin film a-Si:H solar cell studied in this article follows a pin structure. Thin p and n dopped layers of around 10-20 nm induce an electric field on a 200 nm intrinsic layer thus, carriers can move a larger distance before recombination. This so-called collection length (L_c) is at least 10 times greater than the ambipolar L_d of the material [3]. The materials of the device were deposited over a glass substrate that has a Transparent Conductive Oxide (TCO) layer. The front electrode (TCO) is randomly textured in order to scatter the light and it is made up of tin oxide doped with fluorine (SnO_2:F). Following, plasma enhanced chemical vapor deposition (PECVD) technique is used to add the doped and intrinsic a-Si:H layers. Finally, the back contact consists of Al-doped Zinc Oxide (AZO) and an aluminum coating.

Figure 1. Schematic representation of the cross section of the simulated pin a-Si:H solar cell.

3. Simulation tool
Our simulation tool is Sentaurus TCAD. The implemented configurations and the employed parameters are described in reference [4]. The 2D simulated solar cell has the following structure: TCO/p-layer a-SiC:H/i-layer a-Si:H/n-layer a-Si:H/AZO/Al, as depicted in figure 1. The propagation of light was simulated using Monte Carlo Raytracing (RT) in Sentaurus, which needs the complex refractive index (CRI) of all the materials. These values were obtained from reflection, transmission and photothermal deflection spectroscopy measurements. The simulation was performed in the 300-800 nm range, to which a-Si:H is sensitive.

4. Proposed methodology
Based on Basore [5], in diffusive devices it is possible to get the average L_d of the minority carriers plotting the inverse internal quantum efficiency (IQE) in function of the experimental absorption length of the material ($L_{abs} = 1/\alpha$). A linear fitting must be done in the sub-bandgap energy range and the inverse slope would correspond to L_d. This method was extended to flat thin film a-Si:H solar cells, by Tobail et al. [6]. They considered that J_{sc} is proportional to the optical generation (G) and to the collection length [7]. The absorption coefficient ($\alpha(\lambda)$) was obtained experimentally. The photon flux (for each wavelength) at a given depth of the i-layer can be found assuming a Poisson statistical distribution:

$$\phi(d) = \phi_0 exp(-\alpha d), \tag{1}$$

being ϕ_0 the incident photon flux density, and d the depth along the propagation direction of light [8]. Considering that each photon produces one electron-hole pair, the optical generation contribution of each wavelength is:

$$G = \phi_0 \alpha exp(-\alpha d_i), \tag{2}$$

where d_i is the thickness of the i-layer. One may note that generation decreases monotonically, this is because the light intensity diminishes with depth, due to the absorption. However, eq. 2 is not fulfilled in textured cells. Due to light confinement, the average optic path (d_{opt}) in our device is greater than d_i. Additionally, we have to bear in mind the effective absorption of the whole device, which is $1 - R$. Thus we propose the following correction:

$$G = \phi_0 (1 - R) \alpha exp(-\alpha d_{opt}). \tag{3}$$

Regarding eq. 3 and expressing IQE as a function of L_{abs}:

$$IQE = \frac{J_{sc}}{q\phi_0(1-R)} = \alpha exp(-\alpha d_{opt}) \times L_c. \tag{4}$$

We obtain a linear expression for 1/IQE in function of L_{abs} if we take into account the range where L_{abs} is greater than d_{opt}. This can be done because short wavelengths are absorbed before reaching the back reflector. The optical path enhancement can only be experienced by long wavelengths. Therefore:

$$IQE^{-1} = \frac{L_{abs}}{L_c}\left(1 + \frac{d_{opt}}{L_{abs}}\right) = \frac{L_{abs}}{L_c} + \frac{d_{opt}}{L_c}. \tag{5}$$

Here the inverse slope is the average L_c and the y-intercept equals d_{opt}/L_c. We use this last one to obtain the average optical path of light in the long wavelength range. Moreover, since d_i is known we can define the optical enhancement factor (OEF) as:

$$OEF = \frac{d_{opt}}{d_i}. \tag{6}$$

Although we do not know beforehand the value for d_{opt}, we do know that its minimum value at long wavelengths will be d_i. The rays at long wavelengths will rebound at the reflective back contact, therefore we can start the adjustment at $L_{abs} > d_i$ to approximate to the linear range.

5. Results

Since these are field-driven devices, in contrast with Tobail, we suggest that the result of any L_c should be reported as well together with the electric field at which it was obtained. We defined E as the the field at $d_i/2$, which is around 5.90×10^4 V/cm. From the simulation model we obtained a reflection profile for the whole device, and the external (EQE) and internal (IQE) quantum efficiencies at the initial and stabilized states of the cell. A low-pass filter was applied to these raw data, using the moving average of every 10 simulated points. The rms of the extracted noise was not larger than an absolute 1.6% in any of the six simulated curves. In general, the simulated and experimental data agree (see figures 2a) and 2b)). However, the overestimation

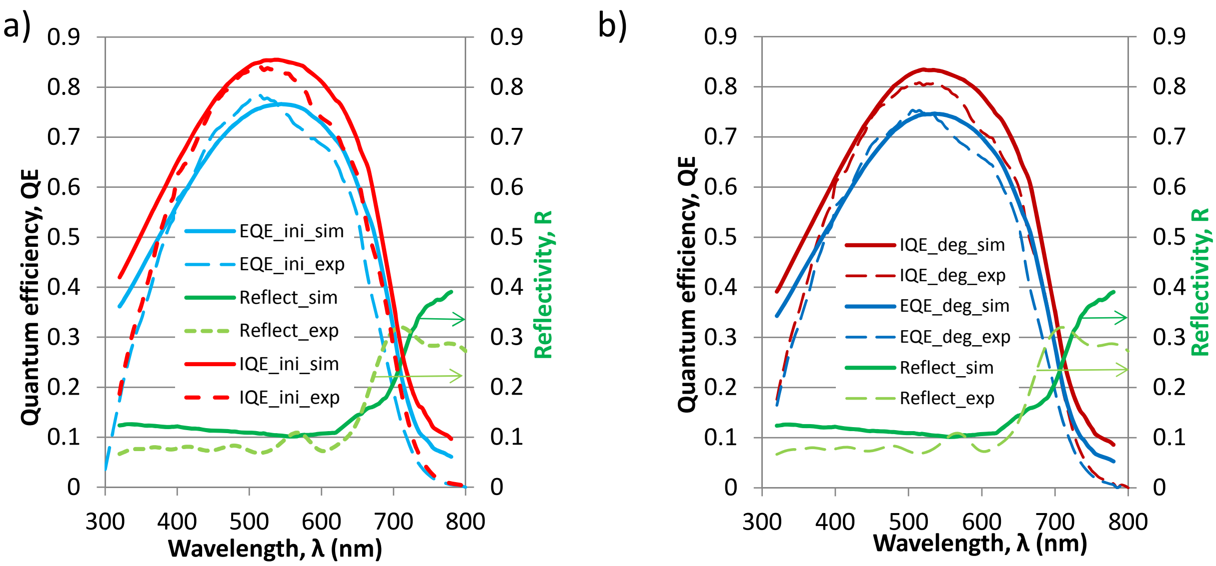
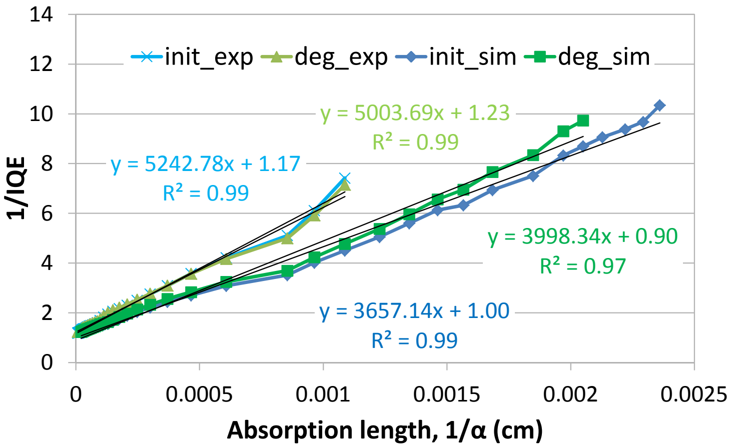


Figure 2. Simulated reflectivity, EQE and IQE in the a) initial and b) degraded state.



Initial	Experimental	Simulated
Lc (um)	1.91	2.73
OEF	11.12	13.67

Degraded	Experimental	Simulated
Lc (um)	2.00	2.50
OEF	12.31	11.25

Figure 3. Inverse IQE against absorption length for the experimental and simulated curves.

at wavelengths shorter than 350 nm can be explained due to the absence of the front glass in the simulation. It was not included due to lack of experimental CRI data. In figure 3 we show the $1/IQE$ versus L_{abs} plot, for absorption lengths greater than the thickness of the intrinsic layer (200 nm). The results for the obtained L_c and the OEF (calculated using equation 6) are summarized in the right part of the aforementioned figure. We found good agreement too. For the device under study, the carriers generated from low energy photons experience an average collection length of 2 μm and the light trapping techniques increase around 12 times the path of light in the long wavelength range (700-800 nm). This factor agrees as well with the expected, because it does not exceed the geometrical Yablonovitch limit ($4n^2$) [9], which averages 60 in the given wavelength range.

6. Conclusions

A noninvasive technique to evaluate the optical and electrical parameters of texturized a-Si:H solar cells is presented. The collection length of the photogenerated carriers under a given electric field can be extracted from the simulated or measured IQE. The optical enhancement factor of the light trapping techniques can also be determined. A collection length of 2 μm (under a 5.9×10^4 V/cm field) was found for the solar cell under analysis. This number is coherent with the expected since it is around ten times greater than the reported diffusion lengths of a-Si:H. For its part, knowing the estimated thickness of the i-layer we calculated an optical enhancement factor of 12, value in agreement with the theory.

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