Impact of series and shunt resistances in amorphous silicon thin film solar cells

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Abstract

In this paper hydrogenated amorphous silicon (a-Si:H) thin film solar cells have been investigated using advanced simulation tools and the obtained electrical values were compared with experimental results. The analysis considers the effects of series resistance and shunt leakage. The simulation tool is parameterized with standard theoretical models for the density of states in the mobility gap, generation/recombination statistics, and experimental optical data of a-Si:H thin films. Experimental measurements were used to implement a textured TCO. Calculation of the illuminated and dark current voltage characteristics for the initial and stabilized states of the ideal solar cell was done. The ideal device was adjusted to the experimental curves using a non-ohmic model for the shunt leakage (simulated as microscopic pip structures, arisen due to aluminum diffusion) and an ohmic series resistance, finding good correspondence. The simulation shows that these mechanisms reduce the cell’s efficiency in around an absolute 1%.

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Keywords: a-Si:H thin film solar cell; Current voltage characteristic; Non-ohmic shunt resistance; Series resistance

1. Introduction

Photovoltaic (PV) modules fabricated with hydrogenated amorphous silicon (a-Si:H) technology have acquired great interest in the last years. This is mainly due to two reasons. First, their fabrication cost is lower to that of crystalline silicon modules, and second, the monolithic serial connection employed for cells results into higher module voltages (Lechner and Schade, 2002). Other advantages of using thin film a-Si:H modules include: enhanced power output under high temperature conditions (due to smaller temperature coefficients), greater absorption of diffuse radiation, and shorter lower energy payback time.

The possibility of using a-Si:H in the production of PV modules on a large scale caused in recent decades a great interest in modeling and understanding the electronic processes that occur in devices made with this material. The involved physical phenomena are complex thus, it has become imperative to use numerical simulation to solve the physical models that describe the operation of such devices. Simulations may help to understand the physical processes that take place during the cell operation and should also allow to determine the mechanisms that limit its performance. Moreover, they are expected to reduce the amount of expensive experimental work and to speed-up the development of new improvements which lead to better properties and lower production costs.

In this work, we present the results obtained in the two-dimensional simulation of single junction (pin) thin film a-Si:H solar cells and its comparison with experimental results, including the influence of shunt leakage and series resistance. In the first part of the paper we introduce the experimental solar cell (Section 2), describe the procedure to obtain the experimental measurements (Section 3) and present the simulated ideal device (Section 4). Next, we
make some comments about the simulation tool and the modifications of the parameterization to simulate an ideal a-Si:H pin structure (Section 5). Following, we analyze the nature of the parasitic currents present in the experimental solar cell (Section 6) and our strategy to simulate them (Section 7). Then, we show the curves calculated for the ideal pin structure (Section 8.1). Following, we describe the results of adding the mentioned defects into the ideal dark (Section 8.2) and illuminated (Section 8.3) $J-V$ characteristics. And finally, in the last section (Section 9), we present the conclusions derived from this work.

2. Thin film amorphous silicon solar cell

The samples described in this paper were manufactured by T-Solar Global S.A. (Grupo T-Solar S.A. Global, 2012), an independent Spanish photovoltaic electricity producer and module manufacturer (Vetter et al., 2009). The production process of these large area ($5.72 \, m^2$) thin film solar modules is based on a-Si:H pin structure deposition on float glass with a Transparent Conductive Oxide (TCO) layer. This process is also known as superstrate configuration because it follows the direction of incident light, in other words, the substrate is above the actual device structure. The back contact of the device consists of Al-doped Zinc Oxide (AZO), and metal coatings which act as reflectors for the non-absorbed light in the first path through the pin structure (Beyer et al., 2007) (see Fig. 1).

The front electrode is a textured fluorine doped SnO$_2$ layer that scatters the light and conducts the current. The doped a-Si:H and intrinsic layers are added by plasma enhanced chemical vapor deposition (PECVD). In T-Solar this system has a cluster configuration; p-layer is deposited in one chamber while i and n layer are deposited in another one to prevent cross-contamination.

The doped layers (p and n) have the function of creating an electrical field through the intrinsic layer (i-layer, where the photocurrent is generated) and of providing a good electrical contact to the end terminals. In the intrinsic layer the light is absorbed and the photogenerated carriers are separated and transported to the corresponding contact. The AZO layer acts as a reflection-enhancing dielectric layer. Lastly, the aluminum metal coating is used as back reflector and contact (Schropp and Zeman, 1999).

It is well known that the a-Si:H exhibits a light-induced degradation during the first illumination hours (Staebler–Wronski effect). This effect causes the creation of new defects (in addition to the initially present dangling bond density) due to the breaking of weak Si–Si bonds (Pankove and Berkeyheiser, 1980). The stabilized (or degraded) efficiency can be around 10–20% lower than the initial one (Staebler and Wronski, 1980). For this reason, in a-Si:H technology, the degraded efficiency is indicated as comparison criteria with the rest of PV devices. The record confirmed stabilized efficiency of a single-junction a-Si:H 1 cm$^2$ solar cell is 10.09%, and was obtained in 2009 by Oerlikon Solar-Lab in Neuchâtel, Switzerland (Benagli et al., 2009).

The impact of the Staebler–Wronski effect on the cell’s response decreases with the i-layer thickness. To achieve a high stabilized efficiency we look for thin i-layers, reason why absorption enhancement techniques (light confinement) are essential (Cannella et al., 2013; Muller et al., 2004). In the analyzed device, the light is confined by introducing a textured front TCO (see Fig. 2) to scatter the light inside the cell. In combination with a high reflecting back contact one achieves longer light paths in the pin structure, which is especially important to absorb light in the 550–800 nm wavelength range (Hegedus and Kaplan, 2002).

3. Experimental $J-V$ curves measurement

With the purpose of improving the efficiency and quality of the modules, T-Solar Global S.A. has installed a scientific laboratory which operates directly beside the production line. Special panels, are produced periodically for
R&D. In them, several coupons (distributed over the surface of the full size panel) are created. Laser scribe method is used to define 10 cells in the coupons, 8 of 1 cm² and 2 of 4 cm². All the measurements used in this paper were performed on 1 cm² solar cells.

Once these coupons are fabricated, two more processes are executed. First, the so-called shunt busting (SB), which is also carried out in the production line for the standard modules, and which consists in the application of 6 V in reverse condition to every cell during 100 ms (with a current density limit of 20 mA/cm²). The second step is an annealing. The samples are placed in an oven at around 145 °C during 30 min attaining a heating cycle similar to the one in the autoclave process completed in the production line. Combining both, SB and annealing, higher efficiencies and smaller variation among cells’ efficiencies are obtained.

Coupons for initial state measurements are kept in dark conditions in the aftermath of their fabrication. Once evaluated in initial conditions, they are degraded in a light soaking station where they receive an irradiation of 300 kWh/m².

To characterize the cells in initial and degraded (stable) states, an automated J–V curve measurement has been developed. A program, adapted to measure both illuminated and dark curves, controls a digital source meter and a precise multimeter. T-Solar’s optical laboratory holds a darkroom maintained at 25 °C.

To measure the illuminated J–V curves under STC (standard test conditions: 1000 W/m², 25 °C, and AM1.5G spectral distribution), a solar simulator (SS) was installed in the laboratory. Its output irradiation is in the range of 950–1050 W/m². In order to reduce the effects of non-uniformity, cells are placed below the optical center of the SS.

Data is corrected to 1000 W/m² measuring a reference solar cell and a reference photodiode. This procedure is done before performing each measurement.

Furthermore, to avoid the increase in temperature (due to the illumination) a cooling system is employed. The temperature is maintained at 25 °C using as well a Pt 100 sensor, which is in contact with the coupon. Measurements are only taken when the cell’s temperature is in the range between 24.5–25.5 °C. Data is corrected to obtain measurements at 25 °C.

4. Simulated device structure

The structure of the simulated solar cell is TCO/p-layer a-SiC:H/i-layer a-Si:H/n-layer a-Si:H/AZO/Al as shown in Fig. 1. For the baseline structure, TCO is tin oxide doped with fluorine (SnO₂:F). We use a-SiC:H for the p-layer because of its wider band gap and higher conductivity in comparison to a-Si:H. This results in a higher built-in potential and allows more light to reach the absorber layer. Therefore, it improves the open circuit voltage as well as short circuit current (Li et al., 2013).

In the simulation, the p-type layer is doped with boron and the n-type layer with phosphorus. To simulate the contacts, we assume an ideal tunnel contact at the front contact and an ideal ohmic contact at the back contact. To implement this, we fix the front contact at the TCO/p-layer interface and the back contact at the end of the Al layer. Hence, in this experiment the electrical features of the TCO are not considered, only its optical characteristics are taken into account.

To determine the open circuit voltage (Vocc) one needs important model parameters, such as the mobility gap of the i-layer and the activation energy of the p-layer (distance between the Fermi level and the valence band edge). The influence of the mobility gap and the effective density of extended states in the i-layer is related to their impact on the maximum possible separation of the quasi-Fermi levels in the i-layer due to optical carrier generation. Since Vocc also depends on the carrier recombination in the device, we observe a strong influence of the band tail parameters and the defect density on the Vocc (Lee et al., 2009).

In what concerns about the short circuit current density (Jsc), it is sensitive to the optical parameters of all layers and to the irradiance level. These values determine the absorption profile in the cell, and Jsc is proportional to the absorption in the intrinsic layer (Lee et al., 2009).

Regarding the fill factor (FF) of the solar cell, this value is sensitive to those parameters which determine the conductivity of the layers (e.g. the activation energies of the pin layers), and to those that control the strength of the electric field across the i-layer (such as tail states and the concentration of dangling bonds) (Stuckelberger et al., 2010).

5. Simulation tool

There are different software packages available in the market for electronic device simulation. Due to its advanced tools we chose Sentaurus TCAD, a software from Synopsys Inc. (Synopsys, 2010). This simulation program uses a standard procedure for semiconducting materials that allows solving the Poisson equation and the continuity current equations including a continuous density of states model and recombination mechanisms such as Shockley–Read–Hall (SRH). Sentaurus is basically designed for simulation of electronic components. Nevertheless, it can be used for the simulation of a-Si:H devices since it is based on semiconductor equations and on physical models that describe the material’s properties. To simulate a-Si:H based elements several configurations must be done. Besides the standard models and equations, the main points to include in an a-Si:H solar cell simulation are (Schropp and Zeman, 1999):

- Theoretical models to describe a continuous density of states (DOS) distribution in the band gap of a-Si:H.
- Model for recombination–generation (R–G) rate and occupation, involving the localized states in the mobility gap of a-Si:H.
• Modeling of heterojunctions.
• Introduction of textured layers (front TCO). Optical modeling including scattering at the rough interfaces.

The Sentaurus configuration used in this paper takes into account all of the precedent points. Their implementation is described in the following subsections.

5.1. Continuous density of states

The continuous distribution of the DOS in the band gap of a-Si:H strongly affects the trapping and recombination processes and therefore, the trapped charge in the localized states cannot be ignored. The standard model of the DOS distribution of a-Si:H consists of a parabolic conduction band (CB), a parabolic valence band (VB), an exponentially decaying conduction band tail (CBT) and an exponentially decaying valence band tail (VBT). These last exponential distributions define the localized states. In addition, two equal Gaussian distributions of states around the midgap are separated from each other by a correlation energy (U) represent the defect states related to silicon dangling bonds (DB+,0 and DB0−) (Cohen et al., 1969; Mott and Davis, 1979; Street, 1991).

5.2. Recombination–generation

In crystalline semiconductors the recombination processes are typically dominated by recombination centers at a single energy level in the band gap. The a-Si:H band gap is characterized by a continuous density of allowed states that contributes to the net R–G rate. Hence, it is necessary to add up (or integrate) the recombination rate contributions from the gap states in the energy band gap. For the non-interacting recombination centers we use the SRH R–G statistics (Shockley and Read, 1952) to model the recombination process.

Additionally, an inherent property of a-Si:H is that it contains amphoteric dangling bond (DB) states (Schropp and Zeman, 1999). These are permitted energy states located near the middle of the bandgap, and can be found in three charged states: positive, negative and neutral. As told before, the DB can be represented as two equal energetic Gaussian distributions in the band gap that are separated by a correlation energy. The transitions between the amphoteric recombination centers and the CB and VB, include eight possibilities:

• Electron capture by a positively charged DB.
• Electron capture by a neutral DB.
• Electron emission from a neutral DB.
• Electron emission from a negatively charged DB.
• Hole capture by a negatively charged DB.
• Hole capture by a neutral DB.
• Hole emission by a positively charged DB.
• Hole emission by a neutral DB.

These multilevel recombination–generation (R–G) statistics were described by Sah and Shockley (Sah and Shockley, 1958). To include them in our simulation, we developed a specific Physical Model Interface (PMI) in Sentaurus (Synopsys, 2010).

5.3. Modeling of heterojunctions

Heterojunctions are described as band-discontinuities that appear at the boundaries among dissimilar materials. In order to smooth these interfaces, we incorporated gradually doped layers between the intrinsic and doped layers. These buffer regions have a dimension of a few nanometers. At the p-layer/i-layer border we added a region with an exponential doping profile which decayed from a $3 \times 10^{18} \text{ cm}^{-3}$ (p-layer acceptor concentration) to $0 \text{ cm}^{-3}$ (i-layer doping concentration). In the case of the gradual layer between the i-layer and n-layer we used a linear profile which increased from $0 \text{ cm}^{-3}$ to $8 \times 10^{18} \text{ cm}^{-3}$ (n-layer donor concentration). Apart from the doping, the rest of the parameters used to simulate these buffer regions were the same as the ones used in the intrinsic layer.

5.4. Textured-layers

As told before, light confinement is essential for obtaining high efficiencies in thin-film a-Si:H solar cells. For this reason, and to have a more accurate simulation, we implemented a textured front TCO based on experimental data.

Atomic Force Microscopy (AFM) measurements were performed on the surface of the on-glass TCO at the Nanotechnology and Surface Analysis Service of Universidad de Vigo (Vigo, Spain). The applied techniques were AFM/STM and Peak Force measurement. The device used was the model Multimode 8 Nanoscope V from Veeco/Digital. The results showed that the texture of the nine examined samples had an average rms (root mean square) value of 43.19 nm and an average peak count of 230 on a surface of 25 µm².

We idealized the surface profile of the TCO as uniform, composed of pyramids. Therefore, in our 2D simulation the texture has been modeled as triangular. The dimensions of the chosen texture were optimized in previous projects (Garcia-Rivera et al., 2012) showing the best performance with a triangular TCO/p-layer interface with a height of 20 nm and a base of 200 nm. For the rest of the interfaces we decreased the height progressively, since we assumed that the roughness will be reduced with the material deposition.

5.5. Optical modeling

In the present paper, the simulation of the light propagation was done by using Monte Carlo Raytracing (RT) in Sentaurus which uses a recursive algorithm. It begins with a source ray and projects a binary tree that tracks
its transmission and reflection (see Fig. 3). This reflection/ transmission process occurs at interfaces with different refractive index. Therefore, RT must be used together with the complex refractive index (CRI) of each region. The CRI is the combination of the absorption and extinction coefficients of the material as function of the incident wavelength. With it, the RT calculates: the incident, reflected, and transmitted components of light through the device (Synopsys, 2010; Lee et al., 2009). The optical data of the a-Si:H layers in our device was obtained from reflection, transmission and photothermal deflection spectroscopy measurements performed at Forschungszentrum Jülich (Jülich, Germany). Moreover, the AM1.5 solar spectrum was used to simulate the current density–voltage ($J–V$) curve under standard one-sun illumination conditions at an intensity of 100 mW/cm$^2$.

5.6. Baseline parameters

Further to this, for a-Si:H layers the critical input parameters such as band gap, doping concentration (conductivity), electron and holes mobilities, the energy distribution of the exponential band tails, and the Gaussian distribution of mid-gap trap states, were chosen based on Schropp and Zeman (1998) and Schropp and Zeman (1999). They are listed on Table 1. The values proposed here are slightly different to the standard values accepted for a-Si:H however, they are adjusted to fit the electrical parameters of a typical 1 cm$^2$ a-Si:H solar cells manufactured in the T-Solar production line. The method to calibrate the adequate set of parameters for our device is explained in chapter 8.1 of Schropp and Zeman (1998).

To simulate the stabilized state (light-soaked state) we only need to increase the maximum density of dangling bonds ($N_{DB}^{tot}$) in the i-layer (Rodriguez et al., 2011; Otero et al., 2011).

6. Solar cells’ defects

In contrast with an ideal diode, the solar cell has limiting mechanisms at high and low biases. Traditionally, these parasitic elements were described as ohmic resistances added to the ideal pin diode. In this model, a parallel (or shunt) resistance $R_{sh}$ was used to represent the undesired high-conductive paths and a series resistor $R_{s}$ (usually smaller than $R_{sh}$) was introduced due to the contact-to- semiconductor interface (Stutenbauer and Mesfin, 1999). Understanding the role of these mechanisms is crucial, since they have a negative impact in the solar cells’ efficiency (Koishiyev and Sites, 2009).

In the forward dark $J–V$ characteristic, the effect of $R_{sh}$ is an undesired current excess at low biases, also known as shunt leakage. On the contrary, $R_{s}$ limits the current at high voltages.

Under illumination conditions, the impact of increasing shunt leakage (or in other words, lowering $R_{sh}$) affects currents in the range between 0 V and $V_{mpp}$, and diminishes the FF of the solar cell. On the other hand, increasing $R_{s}$ reduces significantly the current at biases higher than $V_{mpp}$.

Modeling $R_{s}$ as an ohmic resistance is a good approximation to the experimental behavior of this mechanism. According to the electrical contact model of the metal–semiconductor junctions, p-type semiconductors represent a barrier of only 1/3 of the energy gap of the material (Marinkovic, 2013). Therefore, in the front contact, the energy barrier between the TCO and the p-layer is small enough to be assumed as ohmic. Moreover, in our simulation, $R_{s}$ is considered as independent to temperature and to

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**Table 1**

<table>
<thead>
<tr>
<th>Input parameters used in the simulation.</th>
<th>p-layer</th>
<th>i-layer</th>
<th>n-layer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer thickness (nm)</td>
<td>10–30</td>
<td>200–300</td>
<td>10–20</td>
</tr>
<tr>
<td>Doping (cm$^{-3}$)</td>
<td>$3 \times 10^{16}$</td>
<td>0</td>
<td>$8 \times 10^{18}$</td>
</tr>
<tr>
<td>Relative permittivity</td>
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<td>11.9</td>
<td>11.9</td>
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<td>3.99</td>
</tr>
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<td>Mobility gap (eV)</td>
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<td>1.78</td>
<td>1.80</td>
</tr>
<tr>
<td>Electron mobility (cm$^2$/Vs)</td>
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<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Hole mobility (cm$^2$/Vs)</td>
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<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Effective DOS in CB (cm$^{-3}$)</td>
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<td>$1 \times 10^{20}$</td>
<td>$1 \times 10^{20}$</td>
</tr>
<tr>
<td>Effective DOS in CV (cm$^{-3}$)</td>
<td>$1 \times 10^{20}$</td>
<td>$1 \times 10^{20}$</td>
<td>$1 \times 10^{20}$</td>
</tr>
<tr>
<td><strong>Tail states parameters</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CB mobility edge (cm$^{-3}$/eV)</td>
<td>$2 \times 10^{21}$</td>
<td>$8 \times 10^{21}$</td>
<td>$1 \times 10^{21}$</td>
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<tr>
<td>VB mobility edge (cm$^{-3}$/eV)</td>
<td>$1 \times 10^{21}$</td>
<td>$4 \times 10^{21}$</td>
<td>$2 \times 10^{21}$</td>
</tr>
<tr>
<td>CB tail energy (eV)</td>
<td>0.180</td>
<td>0.032</td>
<td>0.070</td>
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<tr>
<td>VB tail energy (eV)</td>
<td>0.090</td>
<td>0.047</td>
<td>0.160</td>
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<td>Capture cross-section (cm$^3$/s):</td>
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<td></td>
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<tr>
<td>Electron/hole in CB tail</td>
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<td>$10^{-10}$/10$^{-8}$</td>
<td>$10^{-10}$/10$^{-8}$</td>
</tr>
<tr>
<td>Electron/hole in VB tail</td>
<td>$10^{-10}$/10$^{-8}$</td>
<td>$10^{-10}$/10$^{-8}$</td>
<td>$10^{-10}$/10$^{-8}$</td>
</tr>
</tbody>
</table>

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* $a$ The values correspond with the free electron/hole mobility in the extended states.
  * $b$ Capture-rate of holes (electrons) by neutrally charged DB.
  * $c$ Capture-rate of holes (electrons) by negatively (positively) charged DB.

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**Fig. 3.** Scheme of the propagation of the light in the solar cell.
bias voltage. These dependences are included indirectly in the material parametrization itself, reasoned as non-ideal properties of the semiconductor (Otero et al., 2011).

However, this assumption is not accurate for $R_{sh}$. Experimental evidence shows that shunt leakage unfolds much complex features, including: (1) voltage symmetry; (2) non-linear dependence to voltage (power exponent between 2 and 3); (3) weak temperature dependence and (4) large fluctuation from one cell to another (Dongaonkar et al., 2011).

This paper studied the dark $J–V$ characteristic curve of thin-film a-Si:H solar cells, and demonstrated that a space-charge-limited model (SCL) could consistently describe the traits observed in shunt leakage. They provided as well a possible explanation to the physical origin of this phenomenon.

The literature shows that, even with an effective fabrication process control, microscopic high conductive paths arise. These defects are only visible as bright spots in thermography maps (Breitenstein et al., 2002). Thus, the cause of the shunts must be intrinsic to the process. Dongaonkar et al. (2011) suggested that the film surface presents local non-uniformities, such as AZO grain boundaries or areas of high void density in a-Si:H. Consequently, in these regions, Al can diffuse into the thin (about 10 nm) n-layer, counter doping it. Moreover, experimental studies have shown that phosphorous accelerates the Al diffusion behavior (Nagel et al., 1995). The local pip structure that results from this process, exhibits a single-carrier (holes) SCL transport which captures the main characteristic of shunt leakage.

Furthermore, the SCL current through the pip shunt dominates on low biases, while the current on the ideal pin structure takes over at high ones. Having spatially separated currents which prevail at different voltage ranges, enables the possibility to simulate both structures separately. Thermography images show that the typical shunt area is $10^{-4}$–$10^{-6}$ times the area of the solar cell (Kunz et al., 2009). Therefore, simulating the dark $J–V$ characteristic of both elements (pip shunt and pin ideal structure) and knowing this area relationship, allowed Dongaonkar et al. (2011) to obtain the dark $I–V$ characteristic of the solar cell.

In addition, there is evidence that at relatively low temperatures (200 °C to 300 °C), Al may migrate to depths >20 nm (Dongaonkar et al., 2011). This is the temperature range of Al deposition in most thin-film solar cells. Therefore, this thesis was generalized to all thin-film PV technologies (Dongaonkar et al., 2010).

7. Defects simulation

Besides the ideal pin structure we simulated its defects. Our strategy to describe the $R_{sh}$ consisted in applying the method followed by Dongaonkar et al. (2011). We simulated a pip structure with the same area as the ideal pin structure (about 1 μm²). In addition, we used the same simulation parameters as in the ideal pin solar cell (found in Table 1). However, assuming Al migration and counter-doping, we replaced the n-layer in the pin structure for a p-layer. This second p-layer was thicker than the original n-layer (a factor of 10), since we considered that the Al incursion went deeper into the i-layer. The doping concentration used for this region was also greater than the n-layer doping ($8 \times 10^{19}$ cm⁻³). We added as well a buffer layer between the intrinsic layer and the bottom p-layer. Finally, to allow Al incursion we eliminated the AZO-layer on this structure, presuming that the shunt defect was located in an AZO grain boundary. An schematic drawing of the pip simulated structure is shown in Fig. 4.

In the case of $R_s$ simulation, we added an ohmic resistance value to the front contact of 3.50 Ω, which corresponds to the experimental value of the $R_s$ in the TCO/p-layer interface (with an standard deviation of $\sigma = 0.07$ Ω).

We simulated both the ideal pin structure and the pip structure at initial and degraded states, under light and dark conditions, as presented in the next section.

8. Results and discussion

8.1. Simulation results of the ideal pin solar cell

In this subsection we present an analysis of the electrical parameters obtained from the simulations of the a-Si:H thin film solar cells, shown in Section 4.

The continuous lines correspond to experimental data obtained for the typical device manufactured by the end of 2012 in the T-Solar production line. In the other hand, the dashed lines show the $J–V$ characteristics obtained from the simulation of an ideal pin structure with the set of input parameters presented in Table 1.

In the case of the dark $J–V$ characteristic (see Fig. 5), we obtained good agreement between the measured and simulated curves at intermediate voltages. The simulated curves of the ideal solar cell in initial and stabilized states show neither shunt leakage (at low voltages), or series resistance (limiting at high biases).

With reference to the illumination curves, the AM1.5 spectra was used on both, the initial and degraded states.

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Fig. 4. Schematic representation of the simulated pip structure.
As shown in Fig. 6, we achieved a good agreement ($\varepsilon < 1\%$) between the measured and simulated $V_{oc}$ and $J_{sc}$ of a typical 1 cm$^2$ solar cell (both in initial and stabilized states). The main difference with the simulation lays in the FF (10\% smaller in the experimental curves). The results for the electrical parameters are summarized in Table 2.

8.2. Insertion of defects in dark $J$–$V$ characteristic

The following paragraphs describe the results of including $R_s$ and $R_{sh}$ in the simulated curves showed in the previous section. The continuous lines correspond to experimental data and the dashed lines show the $J$–$V$ characteristics obtained from the simulation having the same input parameters as the previous simulation (Table 1).

In Fig. 7 we present the effect of adding an ohmic $R_s$ (3.5 $\Omega$) to the front contact. The simulation of the dark $J$–$V$ characteristic shows that adding $R_s$ in the TCO/p-layer interface limits the current at high voltages.

Regarding shunt leakage, we applied the method proposed by Dongaonkar et al. (2011), where: $$(I)_{cell} = (J_{pin})(A_{pin}) + (J_{shunt})(A_{shunt}).$$ Thus, we fixed $A_{pin}$ as 1 $\mu$m$^2$ and adjusted the simulated curve to the experimental curve modifying $A_{shunt}$. Adding shunt leakage we observe (Fig. 8) a current excess at low biases that adjusts the simulated curve to the experimental one. Comparing the ideality factors ($n$) we see a slight difference between the experimental and simulated curves. In the initial state it equals 1.72 and in the degraded state 1.88. The simulated curve exhibit an ideality factor of 1.61 and 1.70. Differing from the experimental in about 8\% (Table 3).

8.3. Insertion of defects in $J$–$V$ illumination characteristic

In Fig. 9 we present the results of including $R_s$ on the simulated ideal pin structure. One sees that the main variation between Figs. 6 and 9 is located at high voltages, where $R_s$ mechanism is dominant. In comparison to Fig. 6, the efficiency was reduced from 10.14\% to 9.53\% in the initial state, and from 8.94\% to 8.50\% in the degraded state (see Table 4).

Adding shunt leakage (see Fig. 10), the variation of the FF is very significant. One sees that, in comparison to Fig. 9, the efficiency of the simulated cell decreased from and 9.63\% to 9.42\% in the initial state, and from 8.50\% to 8.10\% in the degraded state (see Table 5).

9. Conclusions

In this paper, an amorphous silicon solar cell is described and simulated using Synopsys Sentaurus TCAD tools. The simulated and measured data agree well with respect to the $J$–$V$ characteristics. To include the effects of the series resistance and shunt leakage we added, in the first case, an ohmic resistance in the front contact and in the second case (assuming Al diffusion) we simulated $R_{sh}$ as a microscopic pip structure.

We have implemented the standard models for the DOS distribution and the generation/recombination used in a-Si:H as well as multistate statistics for amphoteric recombination centers. A textured TCO was included to reproduce the light trapping effects in a-Si:H solar cells. Hence, the simulation reproduces well the current voltage characteristics of studied T-Solar a-Si:H solar cells, both in illumination and dark conditions. Simulation results show that cell degradation can be modeled by changing the concentration of dangling bonds in the i-layer.

Simulations of an ohmic series resistance and a non-ohmic shunt leakage describe well the experimental measurements for both, the initial and the degraded state of the solar cell, with and without illumination. This type of analysis was not done before, especially not adjusting both
According to the results, an absolute 1% of the efficiency is lost due to the effect of $R_s$ and shunt leakage. Despite the small area of the pip structures, the simulations show the importance of reducing this defect’s size. The factory with which we collaborated produces 5.72 m$^2$ panels. Therefore, in terms of current loss, the effects are even more significant, thus the importance of having a high homogeneity.

Due to the influence of phosphorus in the Al diffusion, the authors suggest shunt leakage can be reduced by improving the chamber cleaning. If the content in Table 2

Comparison of the electrical parameters obtained from the experimental and simulated cell, in initial and degraded states. Simulated data does not include $R_s$ or $R_{sh}$.

<table>
<thead>
<tr>
<th></th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>$V_{oc}$ (mV)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. initial state</td>
<td>13.65 ± 0.12</td>
<td>929.35 ± 6.34</td>
<td>72.70 ± 0.54</td>
<td>9.22 ± 0.05</td>
</tr>
<tr>
<td>Sim. initial state</td>
<td>13.62</td>
<td>930.95</td>
<td>79.95</td>
<td>10.14</td>
</tr>
<tr>
<td>$\epsilon$ (%)</td>
<td>0.25</td>
<td>−0.17</td>
<td>−9.97</td>
<td>−9.88</td>
</tr>
<tr>
<td>Exp. degraded state</td>
<td>13.26 ± 0.08</td>
<td>895.45 ± 4.69</td>
<td>67.23 ± 0.57</td>
<td>7.98 ± 0.04</td>
</tr>
<tr>
<td>Sim. degraded state</td>
<td>13.39</td>
<td>897.99</td>
<td>74.41</td>
<td>8.94</td>
</tr>
<tr>
<td>$\epsilon$ (%)</td>
<td>−0.93</td>
<td>−0.28</td>
<td>−10.68</td>
<td>−12.03</td>
</tr>
</tbody>
</table>

Table 3

Comparison of the ideality factor obtained from the experimental and simulated cell, in initial and degraded states. Simulated data includes $R_s$ and $R_{sh}$.

<table>
<thead>
<tr>
<th></th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. initial state</td>
<td>1.72 ± 0.09</td>
</tr>
<tr>
<td>Sim. initial state</td>
<td>1.61</td>
</tr>
<tr>
<td>$\epsilon$ (%)</td>
<td>6.25</td>
</tr>
<tr>
<td>Exp. degraded state</td>
<td>1.88 ± 0.08</td>
</tr>
<tr>
<td>Sim. degraded state</td>
<td>1.70</td>
</tr>
<tr>
<td>$\epsilon$ (%)</td>
<td>9.63</td>
</tr>
</tbody>
</table>

Fig. 7. Dark forward $J$–$V$ curves in the initial & degraded states for an experimental (continuous lines) T-Solar solar cell (1 cm$^2$) and the simulated (dashed lines) solar cell, including $R_s$.

Fig. 8. Dark forward $J$–$V$ curves in the initial & degraded states for an experimental (continuous lines) T-Solar solar cell (1 cm$^2$) and the simulated (dashed lines) solar cell, including $R_s$ and $R_{sh}$.

Illumination and dark $J$–$V$ curves, not only in initial but also stabilized state. We can remark as well that we maintained a consistent material parametrization in all cases.
phosphorus of the i-layer is minimum it will prevent further Al incursion. Future research could be performed upon cells with other n-type doping elements.

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References


