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Simulation of forward dark current voltage characteristics of tandem solar cells

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ABSTRACT

The transport mechanisms tailoring the shape of dark current–voltage characteristics of amorphous and microcrystalline silicon based tandem solar cell structures are explored with numerical simulations. Our input parameters were calibrated by fitting experimental current voltage curves of single and double junction structures measured under dark and illuminated conditions. At low and intermediate forward voltages the dark current–voltage characteristics show one or two regions with a current–voltage exponential dependence. The diode factor is unique in tandem cells with the same material in both intrinsic layers and two dissimilar diode factors are observed in tandem cells with different materials on the top and bottom intrinsic layers. In the exponential regions the current is controlled by recombination through gap states and by free carrier diffusion. At high forward voltages the current grows more slowly with the applied voltage. The current is influenced by the onset of electron space charge limited current (SCLC) in tandem cells where both intrinsic layers are of amorphous silicon and by series resistance of the bottom cell in tandem cells where both intrinsic layers are of microcrystalline silicon. In the micromorph cell the onset of SCLC becomes visible on the amorphous top sub-cell. The dark current also depends on the thermal generation of electron–hole (e–h) pairs present at the tunneling recombination junction. The highest dependence is observed in the tandem structure where both intrinsic layers are of microcrystalline silicon. The prediction of meaningless dark currents at low forward and reverse voltages by our code is discussed and one solution is given.

1. Introduction

In multi-junction solar cells and color sensors single p-i-n structures of different band gaps are stacked on the top of each other to reach higher and more stable conversion efficiencies or to conveniently separate the primary colors respectively. Hence multi-junction solar cells have a much more complex structure than single solar cells. The high cost of optimizing these intricate devices by relying on the deposition of numerous samples makes the idea of using computer modeling more attractive as an alternative tool for the improvement of their designs. Modeling of multi-junction devices involves the detailed description of light absorption and electrical transport inside each single p-i-n sub-cell and Tunneling Recombination Junction (TRJ). The approach adopted to describe the electrical transport inside the TRJ differs from author to author [1–4].

All the computer codes that were developed to model solar cells solve the Poisson's and the continuity equations but different authors have adopted different independent variables, solution techniques, descriptions of the density of states, occupation statistics, contact treatments, etc. The author of this paper has built the computer code D-AMPS (AMPS + D = New Developments) based on the well-known software AMPS released by the Pennsylvania State University [5]. The physics of amphoteric states, the Defect Pool-model, the Pool–Frenkel effect, the recombination tunneling as proposed by Hurkx et al., direct tunneling, a simplified light scattering treatment, light interference, and other features have been included into D-AMPS [6–10].

Countless publications where the current–voltage (J–V) of a-Si:H and μc-Si:H based single and hybrid solar cells were evaluated and discussed with device modeling can be found in the literature. On the other hand papers where the light J–V and the spectral response (SR) of multiple junction solar cells were explored with computer codes are less frequent [11–14]. Finally practically no reports on the dark J–V curves of multiple junctions are available.

This paper complements our previous contribution on the forward dark J–V characteristics of micromorph tandem solar cells [15]. In this article the transport mechanisms and the diode factors of the dark J–V characteristics of three different a-Si:H and μc-Si:H based tandem solar cells are discussed. The structures under study are: a-Si:H/a-Si:H, a-Si:H/μc-Si:H, and μc-Si:H/μc-Si:H. Matching of additional experimental data are presented [15]. The inherent difficulties found in the evaluation of the dark J–V curves of multiple junctions at low forward and reverse voltages are also discussed and a solution to this problem is given.

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2. Brief description of the electrical model and experimental information

The density of states (DOS) in a-Si:H and in μcSi:H is described by two exponential tails and three Gaussian distributions recognized by the symbols D^-, D^o, and D^+. The correlation energy U is assumed equal to 0.2 eV. Tails host single donor-like and acceptor-like states while Gaussians host bivalent states. Since there is not a clear picture available for the distribution of energy offsets present at each interface they were equally split between the conduction and valence bands. Flat bands were adopted at both contacts.

The electrical parameters used in our simulations are the result of previous and current efforts of matching experimental J–V characteristic curves of a-Si:H and μc-Si:H single and tandem solar cells deposited and characterized at the Department of Surfaces, Interfaces and Devices of Utrecht University, The Netherlands [3,7,15–18]. In this contribution the most relevant data that were fitted correspond to the dark J–V curves shown in Fig. 1 (some already present in [15]) and to the light J–V characteristics (AM1.5 illumination) listed in Table 1 that were taken from the Marieke van Veen's Ph.D. Thesis [18]. In particular the light J–V of an a-Si:H/μc-Si:H tandem structure, different from the micromorph a-Si:H/μc-Si:H structure of our previous work [15], was also analyzed. The first micromorph cell (fourth line in Table 1) contains a thin defective layer inside the intrinsic layer near the p/i interface that it is not present in the second micromorph cell (fifth line of Table 1). The presence of this defective layer was confirmed by measurements of the Spectral Response (SR) under dark conditions [19]. The most relevant electrical parameters obtained for the a-Si:H and μc-Si:H intrinsic layers are listed in Table 2. The characteristic curves of Fig. 1 and the ones listed in Table 1 correspond to materials grown with the Hot Wire Chemical Vapor Deposition (HWCVD) technique. Nevertheless the dark J–V of an a-Si:H/μc-Si:H tandem cell prepared with the Plasma Enhanced Chemical Vapor Deposition (PECVD) was also included in Fig. 1 for the sake of comparison. Although a considerable portion of this J–V curve (V<1 V) shows shunting problems the data measured at voltages V>1 V are useful for our purposes. The current level is higher in the PECVD sample than in the HWCVD sample due to the lower mobility gap of the a-Si:H and μc-Si:H intrinsic layers. The electrical parameters used at the top and bottom intrinsic layers were also calibrated by matching characteristic curves of single p-i-n samples

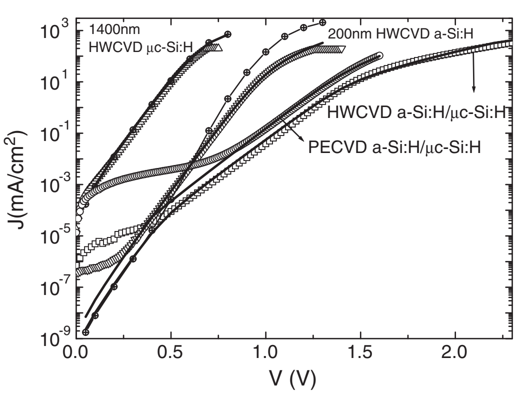

Fig. 1. Fitting (solid lines) of experimental single and tandem dark J–V characteristics. Data of single HWCVD a-Si:H and μc-Si:H p-i-n are shown with open up and down triangles respectively while data of HWCVD a-Si:H/μc-Si:H tandem cell are shown with open squares. The intrinsic layer thicknesses are: 500 nm in the single a-Si:H p-i-n and 1400 nm in the single μc-Si:H p-i-n and 200 nm (top-cell) and 1500 nm (bottom-cell) in the tandem cell. The experimental dark J–V curve of a PECVD a-Si:H/μc-Si:H tandem cell with top and bottom intrinsic layer thicknesses of 250 nm and 1500 nm is also included and shown with open circles. Thinner solid lines with crossed squares (HWCVD) indicate the dark J–V of single a-Si:H and μc-Si:H p-i-n predicted by D-AMPS when the intrinsic layer thicknesses are lowered from 500 nm and 1500 nm to 200 nm and 1400 nm respectively.

Table 1
Comparison of experimental (left columns) and predicted (right columns) Open Circuit Voltages, Fill Factors, Short Circuit Currents and Efficiency of HWCVD a-Si:H and μc-Si:H based single and tandem solar cells. The intrinsic layer thicknesses of each cell in nm are: 400, 1500, 80–500, 200–1500, and 200–1500 respectively. (*) The last tandem cell is the one discussed in reference [15].

Structure	Voc (V)		FF		Jsc (mA/cm^2)		η (%)	
a-Si:H single	0.89	0.9	0.72	0.712	11.2	11.24	7.22	7.21
μc-Si:H single	0.49	0.496	0.628	0.622	14.14	14.13	4.38	4.36
a-Si:H/a-Si:H tandem	1.70	1.70	0.71	0.705	5.7	5.8	6.8	6.9
a-Si:H/μc-Si:H tandem	1.32	1.32	0.64	0.64	7.2	7.3	6.1	6.2
a-Si:H/μc-Si:H tandem (*)	1.38	1.374	0.658	0.658	6.81	6.88	6.2	6.22

[7,16,17]. Some of them are listed in Table 2. The defect density obtained at the bottom intrinsic microcrystalline silicon layer is comparable to the defect density of the very high frequency PECVD μc-Si i-layer measured by Fourier Transform Photoconductivity Spectroscopy. Experimental values of layer thicknesses, global density of states, activation energies, and tail slopes were provided by members of the Utrecht University team.

The Tunneling Recombination Junction used in our simulations contains only μc-Si:H layers. The transport physics is described by the formalism of field dependent cross sections and mobilities as developed by Gu et al. [4,20]. A very thin defective intrinsic layer between the μc-Si doped layers was included in our TRJ junction. In the model proposed by Gu et al. [20] mobilities and cross sections are assumed to hold an exponential dependence with respect to the electric field F as ~exp(F/F_o). The parameter F_o(V/cm) that defines the strength of this dependence has been estimated from our fittings as ~8×10^4 V/cm in the PECVD sample and ~1.1×10^5 V/cm in the HWCVD sample [15]. Both values are comparable to the value used by Willemen in his thesis ($1.2\text{x}10^5$ V/cm) [1]. The high activation energy of the p-a-SiC:H layer (0.47 eV) in the PECVD sample does not have an impact on the experimental dark J–V within the voltage range shown in Fig. 1.

The device structures of the HWCVD and PECVD tandem solar cells fitted in Fig. 1 are as follows: Au/ITO/p-μc-Si/i-a-Si/n-a-Si/nμ-c-Si/AB/p-μc-Si/i-μc-Si/n-a-Si/SS and Glass/SnO_2/p-a-SiC/i-a-Si/n-a-Si/nμ-c-Si/AB/p-μc-Si/i-μc-Si/n-a-Si/ZnO/Ag respectively. The intrinsic layer thicknesses of the top sub-cells are 200 nm (HWCVD) and 250 nm (PECVD) and the intrinsic layer thicknesses of the bottom sub-cells are 1500 nm (HWCVD) and 1400 nm (PECVD). The intrinsic layer thicknesses of the single HWCVD a-Si:H and μc-Si:H cells are 500 nm and 1400 nm respectively.

Using the HWCVD parameters of Table 2 the J–V curves under AM1.5 illumination of five different cells and the dark J–V of four different cells were matched. After calibrating our code, D-AMPS was used to explore the transport physics behind the dark J–V characteristics of three different tandem structures: a-Si:H/a-Si:H, μc-Si:H/μc-Si:H, and a-Si:H/μc-Si:H.

3. Electrical transport mechanisms present in tandem cells under dark conditions

When under dark conditions a forward voltage is applied to the tandem structure its TRJ n-i-p (or n-p) junction becomes reverse biased. Some of the free holes and electrons injected through the front and back contacts are able to cross the top and bottom sub-cells respectively reaching the TRJ. These free carriers are too few to sustain the total tandem dark current. To attain the opposite contacts they need to surmount the adverse potential barriers present at the TRJ boundaries and to travel against the electric field along a second intrinsic layer. In order to maintain the dark current of the tandem structure the reversed biased TRJ thermally generates electron–hole (e–h) pairs; i.e. the TRJ provides extra free carriers that, drifted by