Published in Journal of Non-Crystalline Solids 266-269, 1114-1118, 2000
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Influence of electric field distortion and i-layer quality on the collection function of drift-driven a-Si:H solar cells

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Abstract

A refined analytical model describing the photocurrent collection in amorphous silicon solar cells is presented. Thereby, variations of the electric field within the intrinsic layer are formally taken into account and it is shown that they can be summarized in a 'form factor', φ, which reduces the effective mobility recombination time product of the interior. Based on this model an experimental technique is introduced which aims to determine the transport quality of the intrinsic layer of amorphous silicon solar cells. Two series of cells are analyzed using this technique and the results are compared to transport measurements carried out on equivalent intrinsic layers deposited on glass.

1. Introduction

Current as a function of voltage, I(V), of idealized crystalline silicon solar cells can, to some extent, be analytically calculated [1]. In the case of a-Si:H solar cells, however, it is more difficult to make reasonable approximations by which the non-linearly coupled transport equations can be solved. As a first-order approximation the uniform field approach [2] has been used to describe many of the basic features of photocurrent collection in a-Si:H solar cells [3,4]. Here, we present an analytical approach which takes into account distortions of the electric field. We find that the photocurrent collection function can be expressed in terms of the quality of the i-layer which is monitored by its mobility-lifetime, $\mu^0\tau^0$, product [5]. The variations of the electric field within the i-layer can, thereby, be expressed in terms of a form factor, φ, which reduces the apparent $\mu^0\tau^0$.

2. Constraints on theory

In the following we develop an analytical model with which we estimate the collection ratio of electron hole pairs which are photogenerated in the intrinsic layer of an a-Si:H solar cell. Neglecting the diffusion currents we express the total current (which is constant over the whole i-layer) as

$$j_{\mathrm{tot}} = \mathrm{e}\Big\{\mu_n^0 \cdot n_f(x) + \mu_p^0 \cdot p_f(x)\Big\}E(x). \qquad (1)$$

To calculate the recombination losses we will follow the approach of Hubin et al. [6]. There, it was indicated that under reverse bias conditions, the recombination in a p–i–n diode occurs primarily via neutral dangling bonds (this is certainly the most critical assumption of this model, which limits its applicability to reverse bias conditions).

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The recombination function (describing the recombination occurring via amphoteric states with cross-section ratios $\sigma_n^+/\sigma_n^0 \gg 1$ and $\sigma_p^-/\sigma_p^0 \gg 1$, as present in a-Si:H) can then be expressed as

$$R(x) = \frac{n_f(x)}{\tau_n^0} + \frac{p_f(x)}{\tau_p^0}. \tag{2}$$

In this equation τ_n^0 and τ_p^0 correspond to the capture times of free electrons and holes by neutral dangling bonds: $\tau_p^0 = 1/(v_{\mathrm{th}} N_{\mathrm{db}} f^0 \sigma_{n,p}^0)$.

Additionally, we use an experimental result [5] indicating that, if the dangling bonds were all neutral, the products of the band mobility (μ^0) and the capture time (τ^0) are approximately equal for electrons and holes

$$\mu_n^0 \tau_n^0 = \mu_p^0 \tau_p^0 = \mu^0 \tau^0. \tag{3}$$

Rewriting (1) using (2) and (3) yields

$$j_{\mathrm{tot}} = \mathrm{e} \cdot \mu^0 \tau^0 \cdot R(x) \cdot E(x). \tag{4}$$

From this equation, the recombination rate, $R(x)$, is found to be inversely proportional to the locally prevailing electric field, $E(x)$. Integration of $R(x)$ over the whole i-layer thickness gives the following formal expression for the recombination losses:

$$j_{\mathrm{rec}} = \frac{j_{\mathrm{tot}} \cdot L \cdot \varphi}{\mu^0 \tau^0 \cdot \bar{E}},$$

with

$$\varphi = \frac{1}{L} \int_0^L \frac{\bar{E}}{E(x)} \, \mathrm{d}x \geqslant 1. \tag{5}$$

In this equation, the average electric field is given by $\bar{E} = (V_{\mathrm{bi}} - V_{\mathrm{diode}})/L$, where V_{bi} stands for the built-in potential. The distortion of the electric field is condensed into the form factor, φ, which equals 1 in the case of a uniform field and which increases with the deformation of E. Numerical simulations indicate that $\varphi \leqslant 3$ for reasonable cells [7]. Using this formula, the collection efficiency, the ratio of the collected photocurrent to the generated current is

$$\chi = \frac{j_{\mathrm{tot}}}{j_{\mathrm{gen}}} = \frac{j_{\mathrm{tot}}}{j_{\mathrm{tot}} + j_{\mathrm{rec}}} = \frac{1}{1 + L \cdot \varphi/(\mu^0 \tau^0 \cdot \bar{E})}. \tag{6}$$

We note, on this result, that the collection function, χ, does not contain the light intensity (as long as second-order affects of the generation rate on φ can be neglected). This fact implies that (under reverse bias conditions) the photocurrent is simply *proportional* to the light intensity. This proportionality is in contrast to the (idealized) crystalline case where a *constant photocurrent* is added to the dark $I(V)$-curve [1]. It follows that, for amorphous silicon, the tangents to the $I(V)$ under short circuit conditions measured at different light intensities intersect the abscissa at a unique voltage which we call 'collection voltage' ($V_{\mathrm{Collection}}$, see Fig. 1). In reality, this holds only for an intermediate light intensity range since at smaller intensities the $I(V)$s are dominated by shunts or by the dark $I(V)$ whereas at larger intensities the series resistance has the largest affect [8].

Within the framework of the model presented above $V_{\mathrm{Collection}}$ can be evaluated as

$$V_{\mathrm{Collection}} = I_{\mathrm{SC}} R_{\mathrm{SC}} = \chi \left(\frac{\mathrm{d}\chi}{\mathrm{d}V} \right)^{-1} \Bigg|_{V=0}, \tag{7}$$

where I_{SC} stands for the short circuit current, R_{SC} is the short circuit resistance ($R_{\mathrm{SC}} = (\partial V/\partial I)_{V=0}$). Replacing (6) into (7) results in

$$V_{\mathrm{Collection}} = V_{\mathrm{bi}} \left(\frac{\mu^0 \tau^0 V_{\mathrm{bi}}}{\varphi L^2} + 1 \right). \tag{8}$$

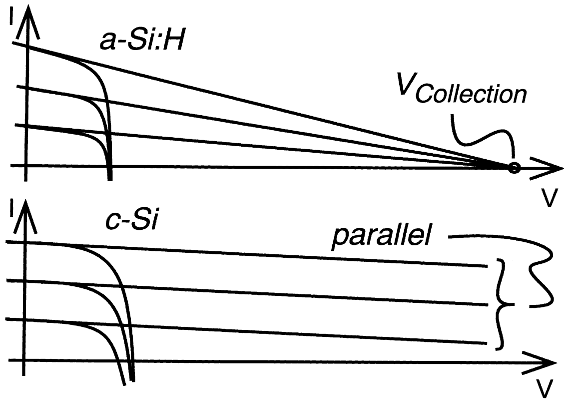

Fig. 1. Schematic representation of the theoretical behavior of $I(V)$-curves of a-Si:H (on the top) and of crystalline silicon solar cells.

Here, V_{bi} corresponds to the built-in potential and L to the i-layer thickness.

Practically, the significance of $V_{\mathrm{Collection}}$ which can be evaluated by measuring $I(V)$ at various light intensities is that, in principle, this quantity can be directly related to the material quality of the intrinsic material monitored by $\mu^0\tau^0$. This statement is to a certain extent equivalent to work published earlier by Merten et al. [8] who introduced the so-called variable-intensity-measurements (VIM) method to determine an 'effective' $\mu\tau$-product from the linear region of a plot depicting R_{SC} vs. $(I_{ph})^{-1}$. Note, however, that here, we have been able to avoid some of the simplifications used in Ref. [8] (we do not assume a linear free carrier profile and we allow for a distortion of the electric field). Additionally, we emphasize the fact that the concept of $V_{\mathrm{Collection}}$ is more general and embraces any model leading to a collection function that is independent of the light intensity (for example the collection model based on the regional approximation [2]).

3. Experimental

In order to evaluate $V_{\mathrm{Collection}}$ and, hence, the i-layer material quality, several procedures can be applied. We can, e.g., measure $I(V)$ at various light intensities and determine R_{SC} by the best linear fit at $V = 0$ V. However, this procedure is not very precise, especially in the case of cells with excellent saturation behavior (see Fig. 2).

For the present work, we developed a measurement set-up (alternative current variable intensity measurement, ac-VIM) with which we evaluate, for different light intensities, directly R_{SC} and I_{SC}. Basically this set-up, which is schematically represented in Fig. 3, consists in applying an alternating voltage to the cell under test (which is biased to zero volts dc) and measuring the resulting alternating current. To obtain a greater precision, this latter is measured, by lock-in technique, as the voltage drop across a known measurement resistor (R_{meas}) connected in series with the cell under test. At sufficiently low excitation frequencies ($\nu = 10$ Hz) the junction capacity can be neglected and the procedure consists in a sweep over $I(V)$ of the cell under short circuit condition.

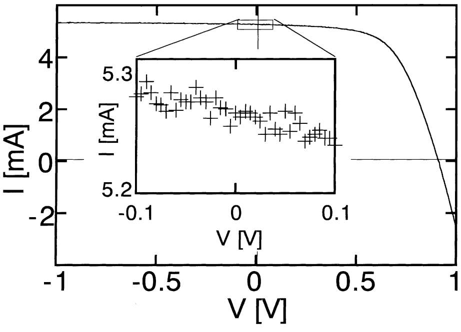

Fig. 2. Measurement of an a-Si:H solar cell with a rather flat $I(V)$-curve at $V = 0$ V.

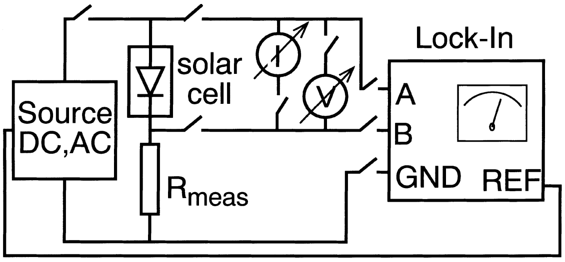

Fig. 3. Measurement set-up used for a precise direct evaluation of the short circuit resistance R_{SC} of a solar cell. Due to the series connection of the cell with a measurement resistor a different (non-zero) dc bias voltage has to be applied by the source for every light intensity to force the solar cell under short circuit conditions. Note that for I_{SC}-measurements the cell is connected directly to a current meter.

4. Results

The described measurement procedure has been applied to two series of a-Si:H solar cells. First, a dilution series consisting of three cells of which the i-layers were deposited using dilution ratios of silane by hydrogen (gas flow ratios $[H_2]/[H_2 + SiH_4]$) of 0, 2 and 9 was analyzed in the initial state as well as after degradation (see Fig. 4). These otherwise identical cells which were deposited at 195°C had an i-layer thickness of 450 nm.

In parallel to the cell analysis, simple i-layers, deposited on glass (corning) using the same

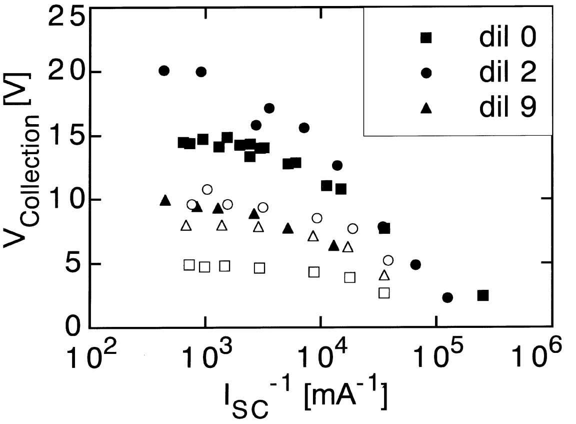

Fig. 4. Collection voltage measurements of a-Si:H solar cells in the initial state (filled symbols) and after light soaking (open symbols). The hydrogen dilution during deposition was varied between 0 and 9. The i-layer thickness was 450 nm for the three cells.

deposition parameters, were measured for the normalized mobility times recombination time product, $\mu^0\tau^0$, according to the procedure described in Ref. [5]. These data allowed a direct comparison between $\mu^0\tau^0$ measured in layers to $\mu^0\tau^0$ measured by $V_{\mathrm{Collection}}$ in solar cells incorporating these same layers. The results are summarized in Table 1.

A second series of solar cells was also analyzed using the described AC-VIM approach. Here, the i-layers were deposited using identical deposition conditions (dilution ratio of 2) but the i-layer thickness was varied between 0.3 and 2 μm. The $V_{\mathrm{Collection}}$ measurements carried out in the initial state are presented in Fig. 5. The series was light soaked during 1000 h by an AM 1.5 source. After degradation $V_{\mathrm{Collection}}$ was measured again as a function of the light intensity (see Fig. 6).

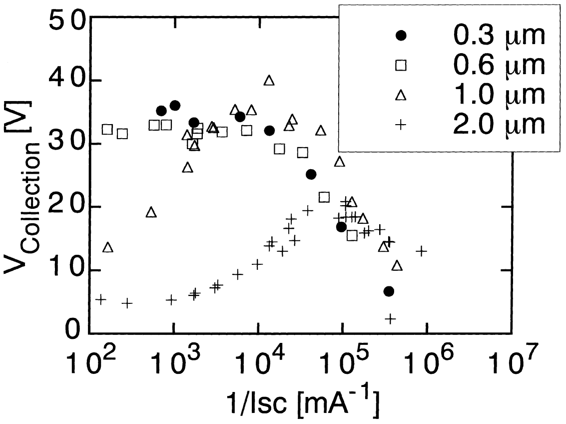

Fig. 5. Collection voltage measurements of a-Si:H cells with variable i-layer thickness in the initial state.

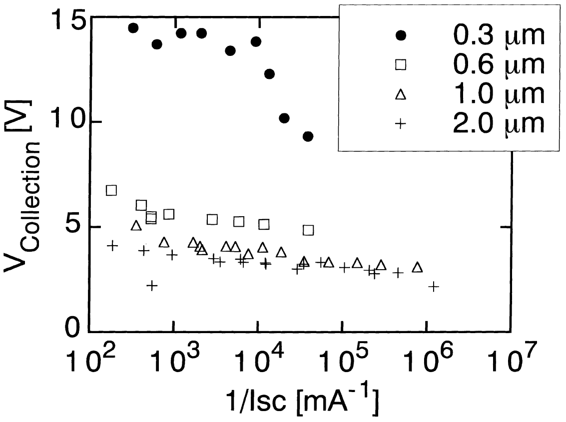

Fig. 6. Collection voltage measurements of a-Si:H cells with variable i-layer thicknesses after light soaking.

5. Discussion

The first interesting observation which can be made, when considering the measurements of the

Table 1
Comparison of $\mu^0\tau^0$-values (cm^2 V^{-1}) measured in i-layers and in solar cells incorporating these i-layers (dilution series)[a]

Dil	$\mu^0\tau^0$ (solar cells)		$\mu^0\tau^0$ (i-layers)	
	Annealed	Degraded	Annealed	Degraded
0	2.2×10^{-8}	0.6×10^{-8}	4.6×10^{-7}	0.5×10^{-7}
2	3.2×10^{-8}	1.4×10^{-8}	7.0×10^{-7}	1.2×10^{-7}
9	1.5×10^{-8}	1.2×10^{-8}	2.3×10^{-7}	1.0×10^{-7}

[a] The form factor was thereby assumed to be $\varphi = 1$.

samples of the dilution series (Fig. 4), is that there is indeed a plateau (of about one-order of magnitude) over which $V_{\mathrm{Collection}}$ remains independent of the light intensity. Comparison between layer measurements and cell measurements reveals, however, a discrepancy between the $\mu^0\tau^0$s. We observe (Table 1) that $\mu^0\tau^0$ measured in solar cells is typically by a factor 10 less than $\mu^0\tau^0$ determined in layers. Nevertheless, it is interesting to us to note that, for this dilution series, both cell and layer measurements have the same trends.

As to the thickness series, we note in the initial state (Fig. 5) that the theoretically expected constant $V_{\mathrm{Collection}}$, over a same intensity range, is only observed for the two thinner cells (0.3 and 0.6 μm). The $V_{\mathrm{Collection}}$ of these two cells are almost equal while, according to Eq. (8), we expect the thinner cell to have a $V_{\mathrm{Collection}}$ four times greater than the thicker one. After degradation (Fig. 6) the ratio between the $V_{\mathrm{Collection}}$ of these two cells is measured to be about three, hence approaching the theoretically expected four. In the case of the thick cells variations of the field deformations could partially be responsible for the atypical $V_{\mathrm{Collection}}$.

6. Conclusions

A new analytical model for the photocurrent collection in a-Si:H solar cells has been deduced. Thereby, we showed how electric field deformations affect the apparent transport quality of the i-layer of the diode by the form factor, φ. We introduced a quantity called $V_{\mathrm{Collection}}$ which is characteristic for any photocurrent collection model that can be described by a collection efficiency independent of the light intensity. An experimental set-up has been described which allows an accurate determination of $V_{\mathrm{Collection}}$. Within the framework of our theory two series of cells were analyzed using the presented method. We found in some cases qualitatively coherent results between cell and layer measurements. Generally, however, we observed considerably smaller $\mu^0\tau^0$-products (by a factor 10) in cells compared to those of corresponding layers.

Acknowledgements

This work has been realized with the financial support by the Swiss federal office of energy under grant 19431.

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