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Microcrystalline p–i–n cells: a drift-controlled device?

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Abstract

The objective of this paper is to get more insight into the physics of microcrystalline silicon based solar cell by studying electric field profiles, spectral responses and current–voltage characteristics. Based on a comparison with a-Si:H p–i–n and c-Si p–n diodes, we concluded that μc-Si:H p–i–n devices are not field-controlled despite the presence of a high electric field in the i-layer.

Keywords: μc-Si:H; Solar cells; Transport properties

1. Introduction

Recent progress has demonstrated that microcrystalline hydrogenated silicon (μc-Si:H) is an attractive material for the active layer of thin film solar cells. Efficiencies of up to 7.7% have been demonstrated on entirely microcrystalline p–i–n cells with no sign of light-induced degradation [1]. Due to the lower absorption coefficient of μc-Si:H for visible light (as compared to a-Si:H), this material requires a thick solar cell (the i-layer thickness is usually between 2 and 5 μm) to absorb the useful part of the solar spectrum.

From spectral response measurements (SR) and current–voltage (I–V) characteristics, it was originally assumed that diffusion plays an important role for the charge collection for these 'thick' devices, when they are operated close to the maximum power point [2]. On the other hand, charge collection measurements (Time of flight (TOF) and spectral response measurements) show surprisingly high collection efficiencies at 0 V applied voltage (short circuit conditions). It is, therefore, interesting to discuss the relative roles of drift and diffusion for carrier collection in μc-Si:H p–i–n (or n–i–p) solar cells, taking into account the measured internal field profiles, I–V characteristics and SR measurements. By comparing these results with known characteristics of a-Si:H p–i–n and c-Si p–n diodes we aim at obtaining more insight into the transport processes involved in these structures.

2. Experimental

2.1. Samples

All μc-Si:H cells were grown by the very high frequency glow discharge (VHF-GD) deposition technique at frequencies between 70 and 130 MHz,

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in a capacitively-coupled parallel plate reactor. Typical deposition conditions may be found in Refs. [1,3]. p–i–n and n–i–p cells were deposited on transparent conductive oxide (TCO) coated glass substrates (Asahi type U) and terminated either with a ZnO or indium tin oxide (ITO) top or back contact to provide a transparent contact on both sides for charge collection evaluations. A special thickness series of p–i–n cells was also deposited in the same run by shielding part of the substrate behind a shutter, to get diodes with various intrinsic layer thicknesses. Current vs. voltage characteristics were performed on p–i–n structures with a back TCO/Ag contact in the dark and under AM1.5 conditions at 100 mW/cm^{-2} using a two-source solar simulator (Wacom WXS-140S-10).

2.2. Electric field determination

To determine electric field profiles in p–i–n solar cells, two methods derive from the charge collection technique known as 'time of flight' (TOF). The first one introduced by Street [4] relies on the current transient of a drifting sheet of charges. Beside the fact that this method has generally a poor spatial resolution (at least with standard TOF equipment), it is in most cases unsuitable for μc-Si:H. As already observed [5,6], μc-Si:H samples exhibit a capacitance which is usually 5 to 10 times larger than the geometrical one. This capacitance induces a RC time constant which tends (in most practical cases) to distort the current transient, and renders this technique very difficult to apply.

The second method, proposed by Vanderhaghen et al. [7], avoids the drawback of Street's technique by relying only on charge collection, without the need to know the exact shape of the measured transients. For this purpose, an external electric field (pulsed, as in the standard TOF system, to insure a homogeneous application of this external field) is superimposed on the internal field. The aim is to create a zero field location at position x_0 in the i layer (cf. Fig. 1), where the internal field $F(x_0)$ is cancelled by the externally applied field, F_{ext}. By changing this external (forward) polarisation, one can change x_0 and, thus, probe the field profile. By measuring the charge collection, Q, and knowing the total photogenerated charge, Q_0 (which can be deduced from the collection under high reverse polarisation) and the sample thickness, L, one can easily determine x_0 where internal and external field are opposite by:

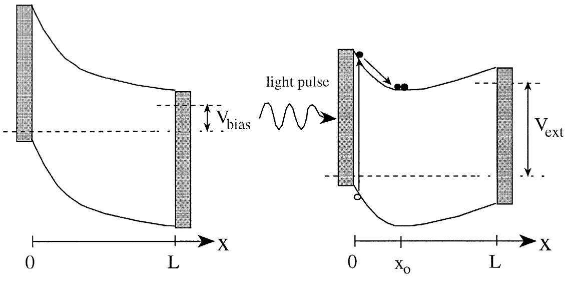

Fig. 1. Cell under bias voltage V_{bias} (usually equal to 0 V) before probing of the internal field (left) and during measurement (right). Zero field location is created at position x_0 where the photogenerated carriers, which have drifted from the front contact, accumulate.

$$Q = Q_0 \frac{x_0}{L} \tag{1}$$

As a matter of fact, this method is 'just' a reinterpretation of the charge collection curve, in terms of internal field distribution. As shown in previous papers [8,9], this technique can be extended when also analysing the hole collection from the other side of the sample (a semi-transparent back contact must be provided for this purpose). A comprehensive discussion of this 'bifacial' method may be found in Ref. [8]. As far as its limits are concerned, one should note that techniques based on charge collection tend to underestimate the field value close to the p–i interface (or n–i interface) due to the charge generation gradient (which must be larger than the doped layer thickness). The latter is directly related to the spatial resolution of the technique. All measurements presented in this paper were performed with an excitation light wavelength of 480 nm, giving an absorption depth of roughly 0.2 μm in μc-Si:H and 0.02 μm in a-Si:H.

3. Results

Measurements of field profiles were performed on the p-side of several p–i–n and n–i–p structures (see Fig. 2). We observe that field values in the central

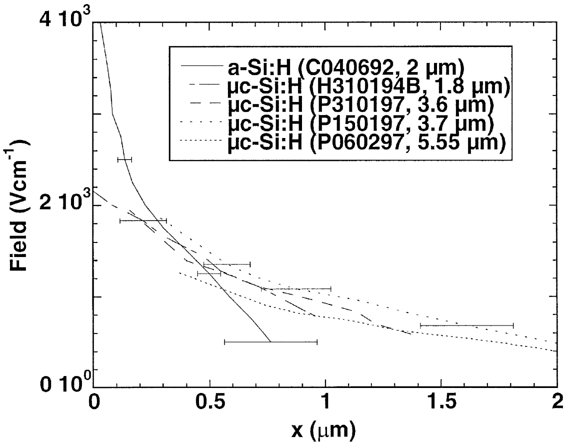

Fig. 2. The internal electric field profile in various thick p–i–n (C040692 and H310194B) and n–i–p μc-Si:H solar cells (field profile of a thick a-Si:H p–i–n cell is given for comparison).

part of the i layer in μc-Si:H diodes are always significantly larger than in a-Si:H ones. In fact, the field distribution in the i layer is different, i.e., more concentrated close to the p–i, respectively, n–i interface in the case of a-Si:H samples.

In Fig. 3, the field profiles of two similar p–i–n cells, but with different i layer thicknesses (1.1 and 2.8 μm) are plotted. We can note that the field values scale reasonably well with the thickness of the i-layer. The integral of the field value over the thickness, which should be equal to the built-in voltage, V_{bi}, gives 0.52 V for the 1.1-μm diode and 0.54 V for the 2.8-μm one. The independence of V_{bi} as a function of thickness is therefore observed. However, this extracted V_{bi} may not be its true value, due to the underestimation of the field close to the doped layers (see above).

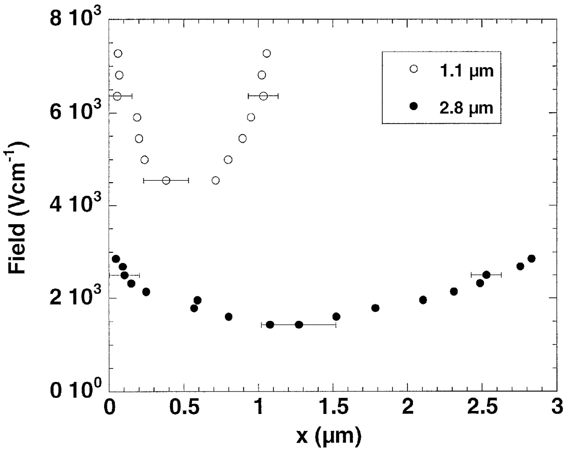

Fig. 3. The internal electric field profile in a series of 2 μc-Si:H p–i–n diodes (deposited in the same run).

4. Discussion

Due to the fact that a-Si:H p–i–n cells are field driven devices, one could easily conclude that μc-Si:H cells which exhibit higher electrical field in the i-layer must operate with the same mechanism. However, the real picture is more complicated.

From a spectral response measurement (external quantum efficiency), one can easily calculate the photogenerated current delivered by the device under some given illumination spectra (i.e., from the convolution of the latter with the quantum efficiency). For a diffusion-controlled device such as a crystalline silicon p–n diode, this photocurrent, I_{ph}^{SR} (calculated from spectral response measurement performed in the dark), is independent of the bias voltage. As a matter of fact, I_{ph}^{SR} is 'just' the difference between the dark current and the total current (under illumination) flowing trough the device at some given bias voltage. As we observe the so-called

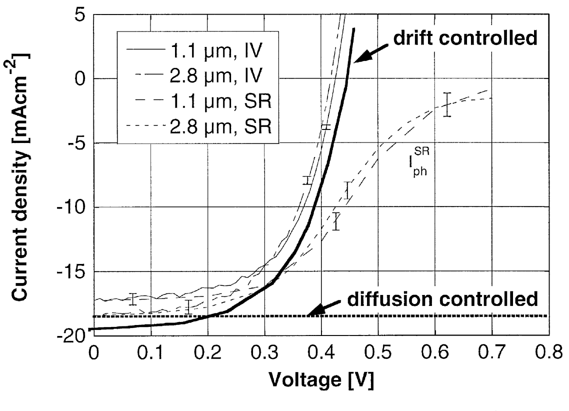

Fig. 4. The current density for 2 μc-Si:H p–i–n diodes (1.1- and 2.8-μm thick) as a function of bias voltage measured directly under AM1.5 100 mW cm^{-2} illumination ($I-V$) as well as current density I_{ph}^{SR} calculated from spectral response measurements (SR), either in the dark or under illumination (I_{ph}^{SR} appears to be independent of the illumination level). The typical behaviour of I_{ph}^{SR} for a drift-controlled device (e.g., a-Si:H p–i–n diode) and diffusion-controlled device (e.g., c-Si p–n diode) is also indicated.

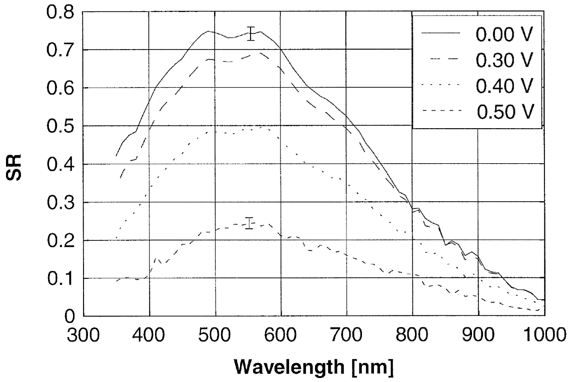

Fig. 5. The spectral response of a 2.8 μm thick μc-Si:H p–i–n diode performed under 30 mW cm^{-2} AM1.5. Under these conditions, the open circuit voltage was around 300 mV. Note that an identical response is observed in the dark.

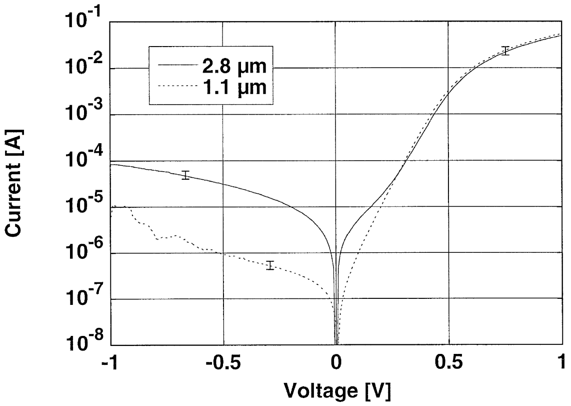

Fig. 7. Dark current vs. voltage characteristics of 2 μc-Si:H p–i–n diodes (1.1- and 2.8-μm thick).

superposition principle in p–n devices, this current, $I_{\mathrm{ph}}^{\mathrm{SR}}$, must therefore be independent of bias voltage (see Fig. 4). We observe in this figure that the behaviour of μc-Si:H p–i–n diode is an intermediate case between a fully diffusion-controlled device and a drift-controlled one. The superposition principle is not valid and $I_{\mathrm{ph}}^{\mathrm{SR}}$ appears to be independent of both the thickness of the intrinsic layer (i.e., no electric field dependence is observed!) and the bias illumination under which the spectral measurements were performed (up to 30 mW cm^{-2}). In contrast with a-Si:H p–i–n diodes, the spectral response of μc-Si:H p–i–n diodes stays positive at almost all wavelengths (the device produces a photocurrent) even for forward polarisation much higher than the open circuit voltage (see Fig. 5). Only for very high forward polarisation or thin diodes does one begin to observe a reversal of the spectral response, starting with smaller wavelengths. As a matter of fact, as we can see when we compare Figs. 4 and 6, the current $I_{\mathrm{ph}}^{\mathrm{SR}}$ is, as for p–n devices, equal to the difference between the dark (see Fig. 7) and total current under illumination.

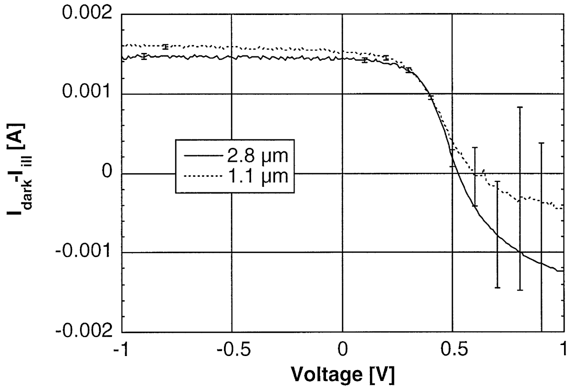

Fig. 6. Difference between the dark and illuminated (AM1.5 100 mW cm^{-2} I–V characteristics of 2 μc-Si:H p–i–n diodes (1.1- and 2.8-μm thick).

Due to limited spatial resolution of the electric field determination method, one should realise that the obtained field profiles are in fact only average profiles, which do not account for the microscopic field distribution. From the increased capacitance observed in μc-Si:H samples (compared to the geometrical one), one expects that the field is concentrated at grain boundaries [6]. Thus, there is the possibility of field driven processes at grain boundaries and diffusion processes inside the grains, which could, in this way, explain the mixed behaviour observed in μc-Si:H p–i–n devices. However, more work will be needed to sustain this hypothesis.

5. Conclusions

Despite a large apparent electric field in the i-layer, μc-Si:H p–i–n diodes exhibit I–V curves and spectral response measurements which differ from those observed in a-Si:H p–i–n devices (which are mainly electric field-controlled), but at the same time also from the behaviour of c-Si p–n devices (diffusion-controlled). These observations imply that these devices are not fully drift or diffusion-controlled, at least for polarisation close to or larger than the open circuit. Given the structure of the μc-Si:H material (small crystallites imbedded in an amorphous tissue) which is by nature inhomogeneous, we assume that drift-controlled transport may occur at grain boundaries, while transport inside the grains is diffusion-controlled. However, the heterogeneity of the material renders difficult both the interpretation of experimental results as well as the confirmation of this hypothesis. For the same reason, only little insight can be expected from simulation work. More work is definitely needed to improve comprehension of these devices.

Acknowledgements

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