Collection asymmetry in a drift-driven p-i-n solar cell

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Abstract

An analytical expression for the voltage dependence of the internal collection efficiency of amorphous silicon p-i-n solar cells is presented. The influence of arbitrary drift lengths (asymmetrical case) is taken into account and it is shown how this asymmetry affects the spectral dependence of the collection. A new experimental technique is proposed to determine the so-called collection voltage. Comparison between preliminary experimental data and theoretical results reveals the limitations of the analytical description.

1 Introduction

In the case of a-Si:H based p-i-n solar cells photocurrent depends on bias voltage (V). It is because in p-i-n structures photocurrent is mainly produced in the i-layer, where the field supports photocarrier collection. The field diminishes under increasing forward voltage. This enhances the recombination and lets the photocurrent decrease.

Various analytical approaches have been proposed to describe the voltage dependence of collection in terms of the quality of the i-layer [1–3]. These models require strong assumptions in order to solve the transport equations. For instance, it is usual to assume that the electric field through the i-layer is uniform and, in many cases, only conditions of weakly absorbed light are considered. Another useful hypothesis is to assume *symmetric collection* [2], i.e., that the drift lengths for electrons and holes are the same. Seemingly, in the case of a-Si:H there is an experimental justification in assuming symmetric collection [4]. However, there is no difficulty about developing the more general case of arbitrary drift lengths (or $\mu\tau$ -products) for electrons and holes.

In this work we review the concept of collection voltage, which is a very useful parameter to evaluate the performance of drift-driven solar cells (see Ref. [2]). We present analytical expressions for the spectral dependence of this parameter in the general case of unequal drift lengths.

2 The collection voltage V_c

A straightforward experiment that demonstrates the sensitivity of photocurrent to the applied voltage is the variable illumination measurement of the short-circuit resistance R_{sc} , i.e., the reciprocal slope of the $I(V)$ curve at the short-circuit point. Over a wide range of illumination levels, R_{sc} is inversely proportional to the short-circuit current I_{sc} . In other words, the $R_{sc}I_{sc}$ -product is independent of the light intensity. This means that the dependence of R_{sc} on light intensity is just counteracted by the dependence of I_{sc} (which should be proportional to the light intensity). Thus, it follows that R_{sc} must be determined by the slope of the photocurrent-voltage curve. The $R_{sc}I_{sc}$ -product

can be evaluated as

$$R_{sc}I_{sc} = \chi \left(\frac{d\chi}{dV} \right)_{V=0}^{-1}, \quad (1)$$

where χ is the internal collection efficiency. The $R_{sc}I_{sc}$ -product has been called collection voltage (V_c) by Hof et al. [2]. The measurement of V_c may be considered as an alternative to the measurement of the internal collection efficiency χ . In fact, equation (1) is valid for many kinds of solar cells. The only requirement is that R_{sc} must be determined by the voltage dependence of the photocurrent; i.e., not by technological factors (e.g., parallel resistance, see Ref. [1]).

In the case of a-Si:H, from analytical descriptions of the collection mechanism in p-i-n structures, plain expressions for V_c have been deduced [1–3]. These models allow to interpret the measurement of V_c in terms of parameters related to the quality of the material of the i-layer (e.g., $\mu\tau$ -products or drift lengths). All these approaches are inspired by the Hubin and Shah’s model [5], whose main assumptions are: (A) uniform field, (B) negligible diffusion and (C) the linear approximation for the recombination function:

$$R = \frac{p_f}{\tau_p^0} + \frac{n_f}{\tau_n^0}, \quad (2)$$

where p_f and n_f are the densities of free carriers, and τ_p^0 and τ_n^0 are the capture times of free carriers by neutral dangling bonds.

There have been attempts to extend this theory to more general situations: e.g., variable electric field within the i-layer [2] and charged defects near the p-i and i-n interfaces [3]. However, perhaps in order to symplify the mathematics, only very particular cases have been studied: low-recombination [3], symmetric

collection ($\mu_p\tau_p^0 = \mu_n\tau_n^0 \equiv \mu\tau^0$ [2]) and, in all cases, *uniformly absorbed light*.

As commented in the Introduction, there is no special difficulty about developing the more general case. In the next Section we show the expressions for χ and V_c in the unsymmetrical case and for non-uniformly absorbed light.

3 Spectral dependence of V_c

We assume an exponential carrier generation profile $G(x)$. For instance, when the cell is illuminated through the p-layer it can be expressed as follows

$$G(x) = \phi_o \alpha \exp(-\alpha x), \quad (3)$$

where α is the absorption coefficient in the i-layer and ϕ_0 is the photon flux at the p-i interface ($x = 0$). As in Hubin and Shah's model, we assume that inside the i-layer bulk recombination is determined by neutral dangling bonds (eq. (2)). This may be valid at the limit of very high illumination (see [3]). Then, considering the three basic assumptions (A-C) explained earlier, the transport equations can take the following form

$$\begin{aligned} L_p \frac{dp_f}{dx'} - p_f(x') - \frac{\tau_p^0}{\tau_n^0} n_f(x') &= -G(x')\tau_p^0, \\ L_n \frac{dn_f}{dx'} + \frac{\tau_n^0}{\tau_p^0} p_f(x') + n_f(x') &= G(x')\tau_n^0, \end{aligned} \quad (4)$$

where the position x' has been normalized to the i-layer thickness ($x' = x/d$) and, L_p and L_n are also normalized drift lengths: $L_p = \mu_p\tau_p^0(V_{bi} - V)/d^2$ and $L_n = \mu_n\tau_n^0(V_{bi} - V)/d^2$ (V_{bi} is the built-in voltage). The boundary condition at the interfaces p-i ($x' = 0$) and i-n ($x' = 1$) are defined by the effective surface-recombination velocities. These velocities for minority carriers are assumed to

be zero. Hence $n_f(0) = 0$ and $p_f(1) = 0$. We can now solve the set of equations (4) and obtain solutions for n_f and p_f . From these solutions we are able to calculate the photocurrent and, dividing by the total generation current in the i-layer, we have the internal quantum efficiency:

$$\chi(L_a) = \frac{\exp(1/L_n) - \exp(1/L_a) \exp(1/L_p)}{(L_a - L_c) (\exp[1/L_a] - 1) (\exp[1/L_n]/L_n - \exp[1/L_p]/L_p)}, \quad (5)$$

where we introduce the normalized absorption length $L_a = \alpha d$ and the L_c parameter (which is similar to the one defined in Ref. [5]):

$$L_c = \frac{L_p L_n}{L_p - L_n}. \quad (6)$$

Finally, differentiating Eq. (5) with respect to the applied voltage and making use of Eq. (1) we obtain V_c :

$$V_c(L_a) = \frac{L_c V_{bi}}{\left(1 - \frac{L_n}{L_p} \exp[-1/L_c]\right)^{-1} - \frac{L_c L_a}{L_c - L_a} + (\exp[1/L_a - 1/L_c] - 1)^{-1}}. \quad (7)$$

From (5) and (7) we can study some particular situations: e.g., the uniform illumination case can be obtained when L_a becomes infinite. Table 1 summarizes some results for these particular situations.

We may note that, when we study from (5) and (7) the spectral dependence of χ and V_c , there are three different behaviours that can be identified according to the relation between L_p and L_n (see Fig.1):

- If $L_p = L_n$ (symmetric case) then χ and V_c are not wavelength dependent.
- If $L_p < L_n$ ($L_c < 0$) then χ and V_c decrease monotonously with growing wavelengths (when L_a increases).
- If $L_p > L_n$ ($L_c > 0$), then χ and V_c increase monotonously with growing

wavelengths.

4 New experimental procedure and results

As we have seen in Secc. 2, the value of V_c is determined by measuring I_{sc} and R_{sc} . Several methods have been proposed to evaluate R_{sc} : e.g., best linear fit of $I(V)$ at $V = 0$ [1] or ac variable-illumination-measurement [2]. However the use of these methods is limited when R_{sc} is affected by parasitic effects. For instance, at high illumination levels the R_{sc} value may be related to the parallel resistance and not to the voltage-dependent photocurrent collection. In this work, we propose a procedure based on measuring directly the photocurrent change when a bias voltage is applied to the device.

We begin with a typical spectral response measurement in which a probe-light of wavelength λ is chopped and the resulting ac current I_λ from the cell is detected by lock-in technique. A photocurrent change dI_λ can be detected when a small voltage dv is applied. Then, according to eq. (1), V_c may be calculated by $I_\lambda dv/dI_\lambda$. We can, thus, obtain the spectrally resolved value of V_c for a given bias-light condition. However, the measurement of the change dI_λ may be not very precise in the case of good cells with high values of V_c . In order to accurately determine dI_λ we propose (as in Ref. [2]) to modulate the applied voltage. The method of measurement is illustrated in Fig. 2. Two alternating signals at different frequencies are applied to the test cell: a monochromatic beam at frequency f_1 and the ac voltage dv at frequency f_2 . With a first lock-in amplifier (LIA1) whose reference is taken from the light chopper (f_1) we detect the photocurrent I_1 (or V_1 in Fig. 2). If f_1 is sufficiently higher than f_2 then, the output from LIA1 can be smoothed by a suitable filter. Thus, this

output is proportional to the alternating photocurrent due to the ac voltage. Measuring the LIA1 output with a second lock-in (LIA2) whose reference is f_2 we can detect the photocurrent change. This method allows an accurate determination of V_c as a function of wavelength and at different bias-light intensities.

Figure 3 shows how the V_c measurement for two typical a-Si:H p-i-n solar cells (cells A and B) varies with wavelength. There are several important points to note (from these very preliminary results):

- V_c is wavelength-dependent.
- This dependence is not monotonous (we find a maximum when the normalized absorption length is about 1).
- V_c is sensitive to the bias-light intensity.

5 Discussion and concluding remarks

By performing a new experimental technique we have obtained preliminary results about the spectral dependence of V_c . These results show that the light wavelength does affect the V_c value. This seems not to be compatible with a symmetric collection model. The asymmetric description (arbitrary drift lengths for electron and holes), in which most of the dangling bonds are in the neutral state, also shows discrepancies: the monotonous wavelength-dependence is not observed in the experimental data.

The analytical model should be refined taking into account some new effects. For instance, it is probable that the charged regions of the i-layer should be taken into consideration. We should note that this assumption, as discussed

in our previous work (see Ref. [3]), could explain the observed sensitivity of V_c to the bias-length.

References

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Figure Captions

- **Table 1:** Specific expressions for χ and V_c deduced from eq. 5 and 7 in some particular cases.
- **Figure 1:** Internal quantum efficiency χ and collection voltage V_c as a function of the normalized absorption length L_a for varying values of the normalized drift lengths. Note that illumination through the n-layer is also considered.
- **Figure 2:** Schematic set-up for the measurement of the spectral dependence of the collection voltage V_c .
- **Figure 3:** Collection voltage measurements for two typical a-Si:H p-i-n solar cells: cell A was deposited at higher temperature. Dashed lines are experimental results under bias-light condition (solid lines are in the dark). For cell A the measurement after light-soaking is shown (A').

Table 1

General Case ($L_p \neq L_n$):	
$\chi(\infty) = \frac{\exp(1/L_n) - \exp(1/L_p)}{\exp(1/L_n)/L_n - \exp(1/L_p)/L_p}$	$\chi(0) = \frac{\chi(\infty)}{L_c(\exp[1/L_c] - 1)}$
$V_c(\infty) = \frac{V_{bi}}{1 - \chi(\infty)/\left\{2L_c^2\left(\cosh\left[\frac{1}{L_c}\right] - 1\right)\right\}}$	$V_c(0) = L_c V_{bi} \left(1 - \frac{L_n}{L_p} \exp[-1/L_c]\right)$
Symmetric Case ($L_n = L_p \equiv L^0$):	
$\chi(L_a) = \frac{L^0}{1 + L^0} = cte$	$V_c(L_a) = V_{bi} (1 + L^0) = cte$
Low-Recombination Case ($\chi \approx 1$):	
$V_c(L_a) = \frac{L_c V_{bi}}{L_c/L_n - L_a + (\exp[1/L_a] - 1)^{-1}}$	
$V_c(\infty) = 2L_n L_p V_{bi} / (L_n + L_p)$	$V_c(0) = V_{bi} L_n$

Fig. 1.

Fig. 2.

Fig. 3.