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NOTE

ANALYSIS OF THE INNER COLLECTION EFFICIENCY IN HYBRID SILICON SOLAR CELLS

Abstract—The collection of photogenerated carriers in hybrid silicon solar cells structures were determined by the DICE (dynamic inner collection efficiency) technique. The hybrid solar cells have a microcrystalline n-type emitter and a crystalline p-type base. Cells with amorphous buffers of several thickness and p^+ back surface field microcrystalline layers were also studied. Spectral response and reflectivity were measured for each sample in order to obtain the internal spectral response or quantum efficiency. These data are the input to DICE analysis, together with the optical parameters of each layer. We observed that the emitter thickness is the most important parameter which defines the solar cell photovoltaic behavior. DICE profiles show that cells with emitter thickness of 80 Å have better collection efficiency than cells with higher thickness values mainly near the surface (until 1 μm below the ITO/microcrystalline interface). The efficacy of the back surface field can be observed with this technique by determining the DICE values near the back metalization and the minority carriers diffusion length can be calculated using the DICE profile in the bulk.

The use of thinner substrates in crystalline silicon solar cells is desirable to fabricate low cost devices. Damages caused by thermal stress during the high temperature impurity diffusion process limit the wafer thickness to about 100 μm[1]. This problem can be solved using hybrid structures in which the emitter is formed by amorphous or microcrystalline layers using low temperature deposition techniques. Standard sputtering at 13.56 MHz[2], Plasma Enhanced chemical vapor deposition (PECVD)[3] and Very High Frequency Glow Discharge (VHF-GD)[4] are the techniques suitable for hybrid devices fabrication at temperatures lower than 600°C.

In this work we studied the carrier collection in hybrid structures fabricated by VHF-GD. The collection of photogenerated carriers inside an hybrid silicon solar cell depends strongly on its structure. This article determines the collection efficiency inside two hybrid solar cells structures using the DICE (Dynamic Inner Collection Efficiency) technique[5,6].

The DICE characterization technique starts from the spectral response measurement to calculate the collection efficiency, the ratio between the incoming photon flux and current density, as a function of the absorption position. The internal spectral response or quantum efficiency, $SR_{int}(\lambda)$, of a solar cell is defined as:

$$SR_{int}(\lambda) = \frac{SR(\lambda)}{1 - R(\lambda)}, \quad (1)$$

where $R(\lambda)$ is the reflection coefficient and $SR(\lambda)$ is the spectral response as measured by the experimental set-up. If we are interested in determining the electrical response of the semiconductor layers, the internal spectral response has to be considered, since it considers the light intensity that effectively is entering the semiconductor structure. The internal spectral response is calculated by;

$$SR_{int}(\lambda) = \frac{J_{ph}(\lambda)}{q\phi(\lambda)(1 - R(\lambda))}, \quad (2)$$

where $J_{ph}(\lambda)$ is the current density at a given wavelength, q is the electron charge and $\phi(\lambda)$ is the monochromatic photo flux.

The current density can be written as;

$$J_{ph}(\lambda) = q\int_0^W D(x)\phi(x)\mathrm{d}x, \quad (3)$$

where W is the total semiconductor structure thickness and $D(x)$ is the DICE parameter, which evaluates the probability of carrier generation at a given point, $x = 0$ corresponds to the first semiconductor layer surface and $x = W$ corresponds to the semiconductor/metal interface in the solar cell back. If $D(x) = 1$, all the incoming photons at the position x generate carriers. If $D(x) = 0$, there is no carrier generation induced by photons absorption at this position.

Combining eqns (2) and (3), the spectral response can be written as;

$$SR_{int}(\lambda) = \int_0^d D(x)\cdot \frac{\phi(x,\lambda)}{\phi(0,\lambda)}\,dx. \qquad (4)$$

The photon flux at the position x has to take into account the reflected beam. It is written as;

$$\begin{aligned}\phi(x,\lambda) &= \phi_i(x,\lambda) + \phi_r(x,\lambda)\\ &= \phi(0,\lambda)(e^{-\alpha x} + Re^{-\alpha(2d-x)}), \qquad (5)\end{aligned}$$

where α is the absorption coefficient, d is the total thickness of the absorption region and R is the reflection coefficient.

In order to calculate the DICE parameter, eqn. (4) has to be written as a summation. The absorption region is divided in m layers. If the spectral response is measured in n different wavelength, the following set of equations will be obtained;

$$\begin{aligned}SR_{int}(\lambda_1) &= \Phi_{11}D(x_1) + \Phi_{12}D(x_2) + \cdots + \Phi_{1m}D(x_m),\\ SR_{int}(\lambda_2) &= \Phi_{21}D(x_1) + \Phi_{22}D(x_2) + \cdots + \Phi_{2m}D(x_m),\\ &\ldots\\ SR_{int}(\lambda_n) &= \Phi_{n1}D(x_1)\\ &\quad + \Phi_{n2}D(x_2) + \cdots + \Phi_{nm}D(x_m). \qquad (6)\end{aligned}$$

Equation (5) can be solved using a matrix formalism:

$$\begin{bmatrix} SR_{int}(\lambda_1) \\ \cdot \\ \cdot \\ \cdot \\ SR_{int}(\lambda_n) \end{bmatrix} = \begin{bmatrix} \Phi_{11} & \ldots & \Phi_{1m} \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \Phi_{1n} & \ldots & \Phi_{nm} \end{bmatrix} * \begin{bmatrix} D(x_1) \\ \cdot \\ D(x_m) \end{bmatrix} \qquad (7)$$

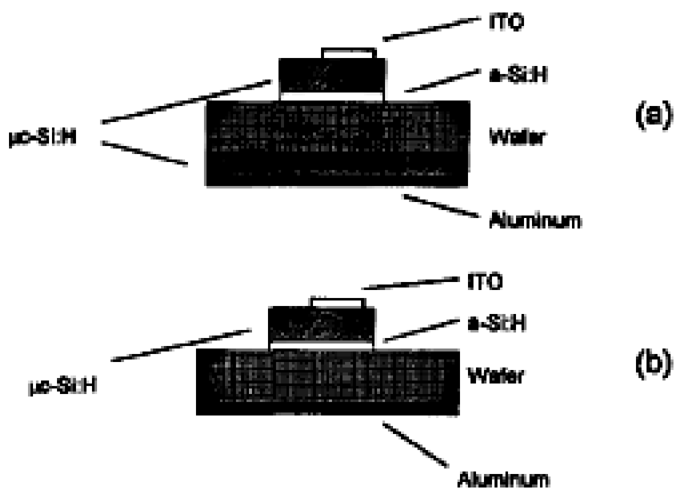

Fig. 1. Hybrid solar cells structures (a) with back surface field and (b) without it.

The matrix equation above is calculated by Singular Value Decomposition (SVD)[7]. The solution domain for the DICE parameter can be tightly controlled by the SVD rank parameter in order to make a correspondence with the measurement solution[5].

Figure 1 shows the structure of the hybrid solar cells studied in this work. The amorphous layer between the microcrystalline layer and the wafer has the purpose of passivating the interface microcrystalline/crystalline. The passivation properties of this layer is confirmed by the increasing in the open circuit voltage, V_{OC}, if compared with results obtained with natural oxide passivation layers.

In the back side of the solar cells the same idea is used. Microcrystalline and amorphous layers are used to make the back surface field and to passivate the interface microcrystalline/crystalline. Figure 1(a) shows the structure with the amorphous layer between the bulk and microcrystalline layer in the back and Figure 1(b) shows the structure without it.

The passivation with the amorphous layer permits to obtain solar cells with high V_{OC} at low processing

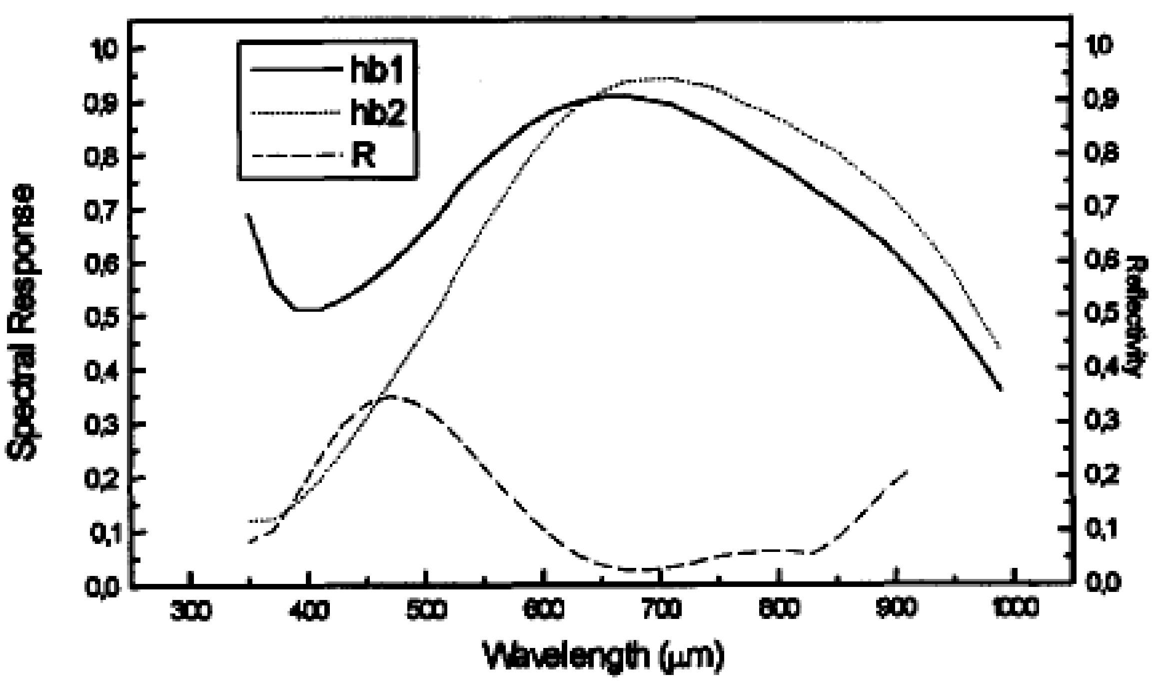

Fig. 2. Spectral response and reflectance of hybrid solar cells.

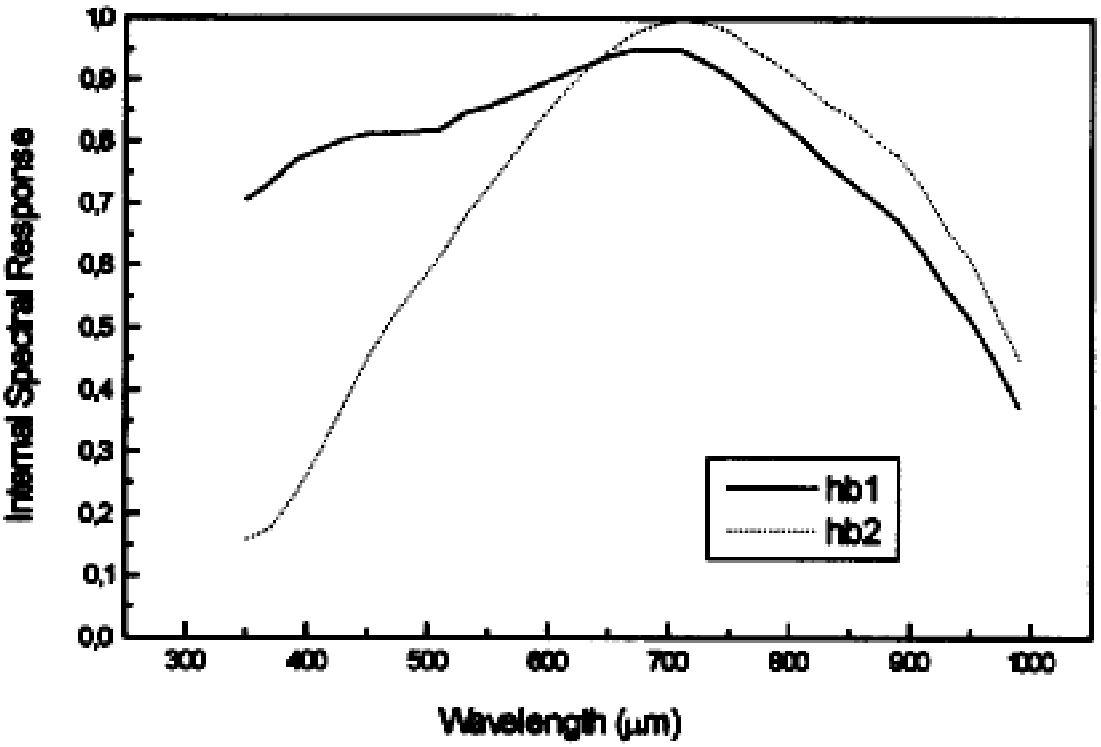

Fig. 3. Internal spectral response of hybrid solar cells.

temperature (typically below 200°C). This is possible because the aluminium is deposited over a highly doped p-type material.

Two solar cells were used for DICE analysis. The cell hb1 has the following characteristics: structure of Fig. 1(a) with n-type microcrystalline layer thickness of 80 Å and amorphous buffer of 24 Å. The cell hb2 has the structure of Fig. 1(b) with thickness of the n-type microcrystalline layer of 540 Å and amorphous buffer of 72 Å. The floated zone p-type silicon wafers used in both cells are 250 μm thick, with a resistivity of 0.5–1 $\Omega \cdot$ cm.

Figure 2 shows the spectral responses and reflectance of these cells. These data are used to calculate the internal spectral response, SR_{int}, as given by eqn (1), shown in Fig. 3. The reflection coefficient is mainly determined by the ITO layer and ITO-microcrystalline interface.

Figure 4 shows the DICE profiles for the two measured cells. A logarithmic scale has been used in the x-axis to emphasize the DICE values near the solar cells front surface, where the most part of the carriers are collected.

The DICE analysis of hybrid solar cells requires the utilization of three different optical absorption coefficients. The optical absorption in crystalline materials is well known and curves in function of the doping concentration are available[8]. Hydrogenated

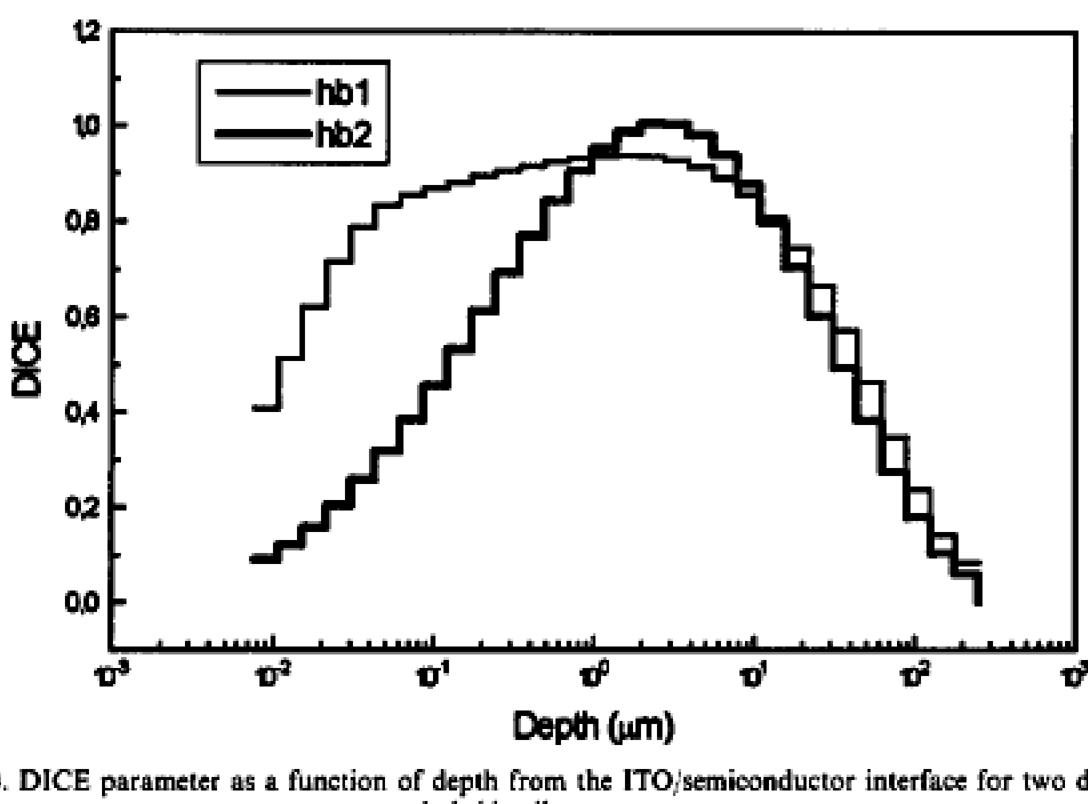

Fig. 4. DICE parameter as a function of depth from the ITO/semiconductor interface for two different hybrid cell structures.

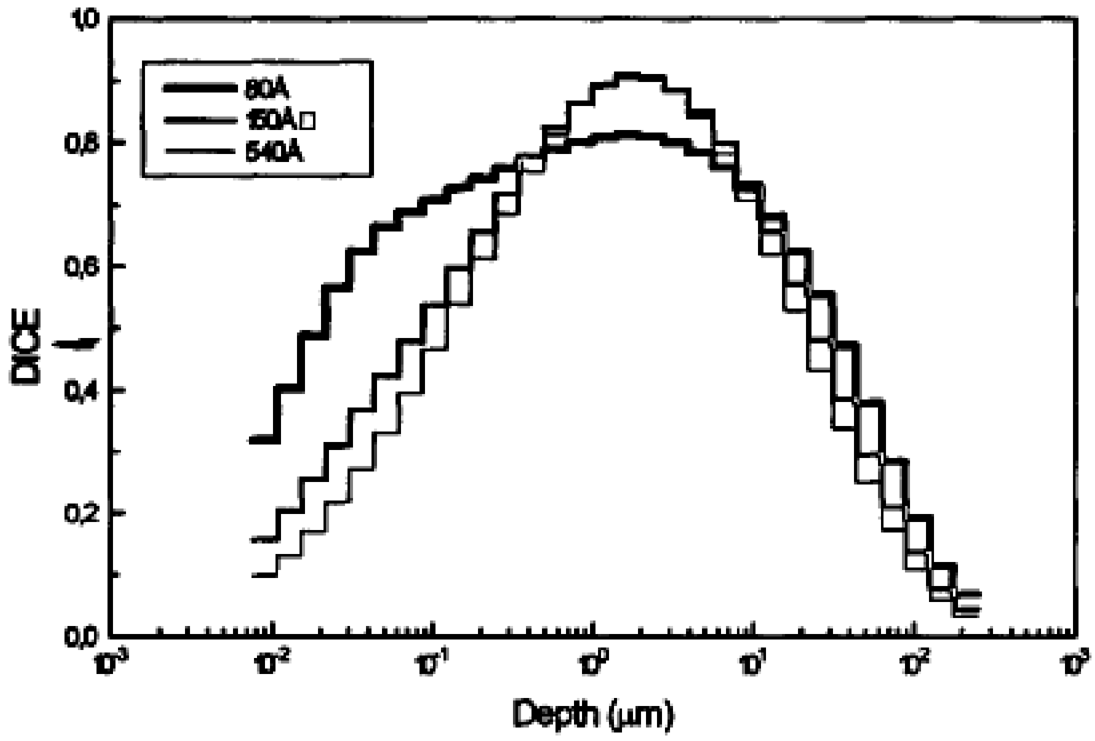

Fig. 5. DICE profiles for hybrid cells with different emitter thickness.

amorphous silicon has greater optical absorption in the range 300–700 nm if compared to crystalline material[4] and microcrystalline materials absorb more than the two other in the entire wavelength range[9].

Figure 4 shows that 1 μm below the surface, the collection efficiency is higher for cell hb1. For distances from 1 to 100 μm, cell hb2 is more efficient and for distances above 100 μm, cell hb1 generates higher currents than cell hb2.

The poorest absorption of cell hb2 below 1 μm is caused by losses in microcrystalline layer. Very high defect states concentrations in this region enhances the recombination of photogenerated carriers and decreases its collection efficiency. In this case, a very thin *n*-layer is recommended. Otherwise, the thick microcrystalline layer in the solar cell back seems not to generate an effective back surface field, since the collection efficiency of cell hb1 in this region is higher.

Figure 5 shows the DICE profiles for structures detailed in Fig. 1(b) for three different *n*-type microcrystalline emitter thickness. These data can be compared with the photovoltaic measured parameters for these cells. The short circuit current J_{sc}, and open circuit voltage, V_{OC} and fill factor, *FF*, in Table 1. The solar cell with the smallest emitter thickness has the higher short circuit current, 28.6mA cm^{-2}. Otherwise, the better open circuit voltage of the cell with the emitter thickness of 540 Å has the better open circuit voltage, 615 mV. This fact suggests that the junction quality, defined by its abruptness and the concentration of trap states in the depletion region, in this case is better.

The effect of series resistance can be seen analyzing fill factor data. The series resistance increases as the fill factor decreases[10]. The fill factor data shown in Table 1 show a slight increase in the series resistance as the emitter thickness decreases.

In conclusion, this work shows the applicability of a DICE analysis in hybrid solar cells. This analysis is particularly useful to set fabrication parameters, as the thickness of film layers. From simple spectral response measurements we can characterize the different parts of a solar cell structure. The collection efficiency near the surface, in the bulk and in the back can be calculated using appropriate optical models.

DICE analysis for hybrid solar cells are useful to calculate the appropriate thickness of the *n*-type emitter microcrystalline film and the efficacy of the buffer amorphous layers and BSF microcrystalline layers.

We concluded that the sample with a thinner emitter has better performance. The solar cells analyzed in this work use crystalline wafers 250 μm thick. For these samples, the BSF is not effective.

DICE analysis can also be used to calculate the minority carriers diffusion length in the base of an hybrid solar cell.

Table 1. Photovoltaic parameters for hybrid solar cells with different emitter thickness.

Emitter thickness (Å)	J_{sc}(mA cm^{-2})	*FF*	V_{oc}(mV)
80	28.6	0.64	600
100	27.6	0.68	582
540	23.6	0.69	615

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