

Effects of the Back Reflector on the Optical Enhancement Factor and Quantum Efficiency of a-Si:H p-i-n Solar Cells

Ruhi KAPLAN, Bengü KAPLAN

Department of Physics, University of Mersin, 33342 Mersin-TURKEY

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Abstract

The effect of tin oxide (SnO_2) texture and back reflector (BR) on optical enhancement factor has been extensively investigated in a series of 4 a-Si:H p-i-n solar cells. The internal quantum efficiency QE in the wavelength range 550–750 nm has been analyzed using an optical model. The optical enhancement factor m , which is a wavelength-dependent fitting parameter, represents the increase in optical pathlength relative to the i-layer thickness. Our solar cells, at low or high haze SnO_2 with an Al BR, have negligible optical enhancement, $m < 1.5$, representing failure to obtain multiple reflections. This is consistent with large parasitic absorption at the Al/Si interface. Our solar cells at high haze SnO_2 with ZnO/Al or ZnO/Ag BRs have peak values of $m \sim 3 - 4$, with ZnO/Ag having slightly larger values than ZnO/Al. The maximum values of m , and thus the QE increase with reflectivity of the BR, indicates that efficient light trapping needs a very reflective BR to minimize parasitic absorption losses with each pass.

PACS numbers: 84.60.Jt, 78.65.-s, 72.40.+w. **Key words:** amorphous (a-) Si:H p-i-n solar cells, back reflectors, light trapping, quantum efficiency.

1. Introduction

The conversion efficiency of photovoltaic devices depends strongly on the ability of the solar cell to absorb a significant fraction of the incident light. In order to increase the absorption of the incident light in a-Si:H p-i-n solar cells, light trapping techniques [1] play a major role. The term ‘light trapping’ is used to describe methods to capture the light in a desired part of the solar cell and preventing it from escaping. In order to keep the light inside the solar cell include the introduction of textured substrates and efficient back reflector (BR). The utilization of textured substrates leads to a large suppression of optical loss due to reflection at the front of the solar cell and the implementation of a BR minimizes the transmission loss into the back contact of the solar cell. Though several workers [2, 3, 4, 5, 6] have investigated textured tin oxide (SnO_2) surfaces with different BRs, we still do not fully understand their exact functions and the roles of their constituent layers.

In this work, we present results from our optical modeling work based on the analytical method of Schade and Smith [7]. We analyze the effect of light trapping on quantum efficiency QE and optical enhancement factor m for our a-Si:H p-i-n solar cells deposited on textured SnO_2 substrates with different types of BR (Al, ZnO/Al, ZnO/Ag). Comparing the results of the optical modeling with our own experimental data, we show that the maximum values of m and QE increase with reflectivity of the BR used. These results imply that the efficient light trapping requires a very reflective BR to minimize parasitic absorption losses.

2. Experimental

Single junction a-Si:H p-i-n solar cells were deposited by RF plasma CVD. The substrates were 7059 glass that had previously been coated with textured tin oxide (SnO_2). The cell structure was: glass/textured tin oxide/(a-SiC:H) p-layer/(undoped a-SiC) buffer-layer/(a-Si:H) i-layer/(a-Si:H) n-layer/BR, as shown in Figure 1. The thicknesses of the p-, buffer-, i- and n-layers were 15 nm, 15 nm, 920 nm, and 20 nm, respectively. For our each run, there were four substrates. Three of them were highly textured SnO_2 (Asahi type U) and the fourth was lightly textured SnO_2 . Thereafter they will be respectively referred to as HTX and LTX. Their thicknesses were $0.8\mu\text{m}$ and $0.4\mu\text{m}$, respectively. The solar cell devices were completed by depositing a BR contact. Three different BR configurations were used here. One piece on HTX SnO_2 and one piece on LTX SnO_2 received Al contacts, while the other two HTX substrates received ZnO/Al and ZnO/Ag contacts. The ZnO was sputtered in Ar/O_2 at 3 mT. The thickness was 80 nm. The Al and Ag were thermally evaporated. The solar cell areas were 0.4cm^2 .

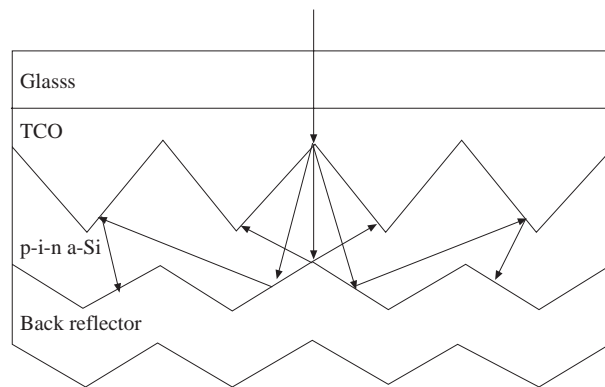


Figure 1. Schematic diagram of light trapping in an a-Si:H p-i-n solar cell.

The details of optical (absorption, transmission and reflection) and electrical (current-voltage and QE) measurements, which we need for a quantitative analysis of the QE and m (optical enhancement factor), have been given elsewhere [8].

3. Optical QE Model

Figure 1 shows a schematic representation of light trapping in a convenient a-Si:H solar cell. As will be seen, the incident light passes through the glass and the transparent conductive oxide (TCO) coating and arrives at the textured interface with the silicon. Due to the texture a fraction of light is scattered into the silicon layer under various angles. The light that is not absorbed in the silicon layer arrives at the back contact. The light that is transmitted into the back metal contact is an optical loss and therefore the reflectance of the silicon/back contact interface has to be maximized. This is accomplished by adding a thin TCO layer between the n-type a-Si:H and the Al or Ag layer. The TCO and metal layer then form the back contact. The interface between the silicon and the back contact is also rough and causes scattering of a part of the light that is reflected at this interface. The reflected light passes through the silicon back to the TCO/a-Si:H interface. Since the refractive index of a-Si:H is higher than the refractive index of TCO, the fraction of the light arriving at this interface from the a-Si:H side under an angle greater than the critical angle is reflected back into the silicon layer. The light can thus pass several times through the a-Si:H layer. The combination of the internal reflection at the TCO/a-Si:H interface with the highly reflective back contact leads to light trapping in the a-Si:H layer.

The critical aspect in modeling the optically limited QE is to calculate the light absorbed in the i-layer of solar cell due to light trapping (see Figure 1). This includes accounting for optical losses which occur before the light enters the i-layer. Following Schade and Smith [7], the QE can be written as

$$QE = (1 - R_F)(1 - A_{TCO})(1 - A_p)(A_i) [1 + f(R_B)], \quad (1)$$

where A_{TCO} , A_p , and A_i are the absorbance of the TCO, p-layer, and i-layer, respectively, and $f(R_B)$ is the enhancement due to the back reflection.

A fraction of the incident light is reflected from the air/glass, glass/ SnO_2 , and SnO_2 /p interfaces before having a chance to be absorbed in the p-layer or i-layer. The reflection from the smooth glass and glass/ SnO_2 is specular while reflection from the SnO_2 /p can be specular and diffuse. These three components of the front surface reflection are grouped together as R_F .

Light is also absorbed in the $SnO_2(A_{TCO})$ and in the p-layer (A_p). The p-layer absorption coefficient was determined from the measured transmission and reflection of the a-SiC p-layer [8]. The absorption loss in the p-layer dominates the QE at short wavelengths and is negligible beyond 600 nm, where the analysis of the optical enhancement is focused. The absorption in SnO_2 is relatively flat and only a few percent in the range of interest for this study. Thus, the fraction of incident light reaching the i-layer is given by the product of the transmission through each of the front window layers, or

$$T_i = (1 - R_F)(1 - A_{TCO})(1 - A_p). \tag{2}$$

This quantity agrees very well with the measured QE up to where the QE begins to decrease due to fall-off in the i-layer absorption.

A ‘figure of merit’ that can be used to assess the performance of the light trapping system is the optical enhancement factor m . m is defined as the increase in the effective absorption due to light trapping. Since m depends on scattering, absorption and reflection, which are all wavelength-dependent, m must be wavelength-dependent as well. Thus, the absorption in the i-layer is given by

$$A_i = 1 - \exp(-\alpha md), \tag{3}$$

where α is the i-layer absorption coefficient, and d is the i-layer thickness of the cell.

Rearrangement of the expression of Schade and Smith [7] gives the contribution of the back contact to the enhancement as

$$f(R_B) = R_B(1 - A_i) = R_B \exp(-\alpha md). \tag{4}$$

Here, the absorption in the n-layer is neglected.

Our optical modeling proceeds by using measured values of all parameters except m which was then adjusted at each wavelength to obtain the best agreement between the measured QE and Equation (2) in the range from 550 nm to 750 nm. R_B is reported to be nearly independent of wavelength [7, 8]. We constrained m to be between 1 and 20 and R_B to be between 0.2 and 1, and adjusted their values using increments of 0.1 and 0.05, respectively. Parameters m and R_B were adjusted until agreement between the measured QE and Equation (2) was within 1% (relative) if possible. Typically this criteria was met at all wavelengths, except at the shorter wavelengths on our 4 thick devices where the light had not penetrated to the back contact ($\alpha d \gg 1$) and there would be no enhancement. In these cases, the model would have difficulty fitting the measured QE within 1% since, in that case, the QE is independent of m and R_B .

4. Results

Table 1 shows the illuminated current-voltage (J-V) performance for 4 solar cell pieces with different SnO_2 and BR under simulated AM1.5 global light from an Oriel solar simulator. Here, R_{OC} represents the resistance at open-circuit. The last column shown in Table 1 are values of the QE integrated with the AM1.5 spectrum.

Table 1. Illuminated J-V performance for 4 solar cell pieces with different BR on LTX or HTX SnO_2 .

SnO_2 haze	BR contact	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	Eff (%)	R_{OC} ($\Omega \cdot cm^2$)	Integral QE (mA/cm^2)
LTX	Al	0.83	13.01	59.4	6.4	10.3	13.68
HTX	Al	0.83	14.0	65.8	7.6	6.3	14.42
HTX	ZnO/Al	0.83	15.02	66.9	8.3	5.6	15.12
HTX	ZnO/Ag	0.80	15.09	69.3	8.4	5.3	15.20

The QE was measured from 400 nm to 750 nm using a lock-in detector chopped at 70 Hz, illuminated through a monochromator having 12 nm width at half maximum. The QE was measured with a reverse bias voltage to establish a sufficiently high field in the i-layer so that the QE saturated. Thus every photon absorbed in the i-layer generates a carrier which is collected. In other words, electrical losses were negligible. The amount of applied reverse bias necessary for saturation of the QE was -4 V. Figure 2 shows the QE vs wavelength for four solar cells with different textured SnO₂ and BR. Obviously the cell with LTX SnO₂ differs from the other three on HTX SnO₂ due to interference fringing. It has a lower QE at short wavelengths because of the large reflection fringe [8]. This is in agreement with the other reports of solar cells on smooth substrates having lower blue response due to increased front surface reflection surfaces [5, 9]. The cell on LTX SnO₂ also has a more pronounced interference fringe at longer wavelengths due to the greater specular reflection [8]. As seen in Figure 2, the long wavelength QE increases going from LTX to HTX, and from Al to ZnO/Al to ZnO/Ag BR. In the following, we will focus on the wavelength region from 550 nm to 750 nm, where the optical enhancement takes place.

Figure 3 shows the measured and calculated QE vs wavelength for all 4 cell combinations together. As will be seen, there is a good agreement between measured and fitted QE. For the fitted (calculated) data, we used a fixed value of R_B , with values of $R_B = 0.7$ for Al, 0.82 for ZnO/Al, and 0.87 for ZnO/Ag. These numerical values were obtained from the measurements of BR test structures [8]. The decision to use fixed values of R_B was based on the lack of significant difference between fixed and fitted data. It is also consistent with other results [7, 10].

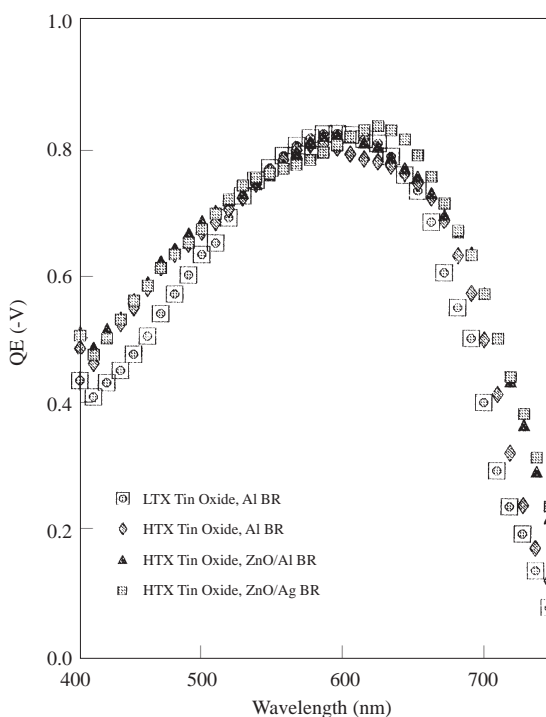


Figure 2. QE (-V) versus wavelength for solar cells with all four combinations of SnO₂ and BR.

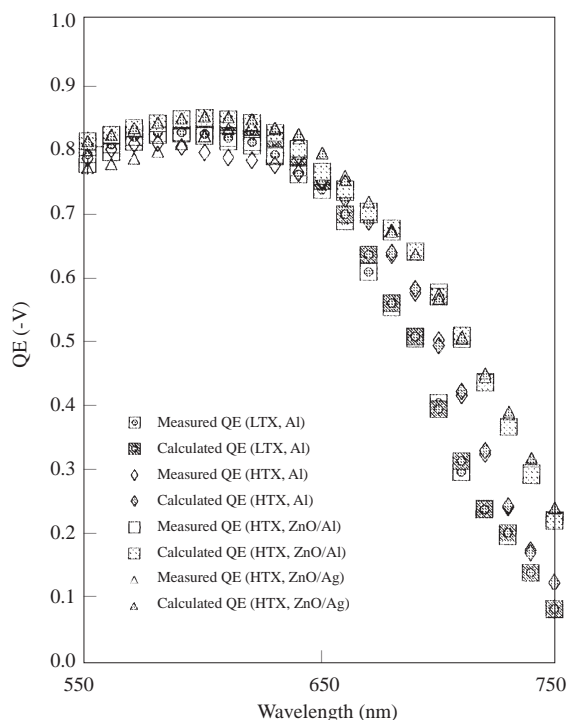


Figure 3. Measured and calculated QE (-V) versus wavelength for solar cells with all four combinations of SnO₂ and BR.

Figure 4 shows m vs wavelength for each piece of solar cell used. Clearly, above about 600-650 nm, there is little optical enhancement with the Al BR for either the LTX or HTX SnO₂. The m values are generally less than 1.5 with Al contacts on the LTX or HTX substrates. This implies a strong reduction in multiple passes because of Al BR. For the cells with ZnO/Al and ZnO/Ag BR, m increases monotonically up to $m \sim 3 - 4$ with increasing wavelength. However, below about 600 nm, there is almost no optical enhancement for all cases. It indicates that the light is still being strongly absorbed in this wavelength region (550-600 nm), and the model used here does not strictly apply. Figure 4 also implies the critical

importance of the ZnO buffer layer between the Si and metal layers for improving optical enhancement of the QE.

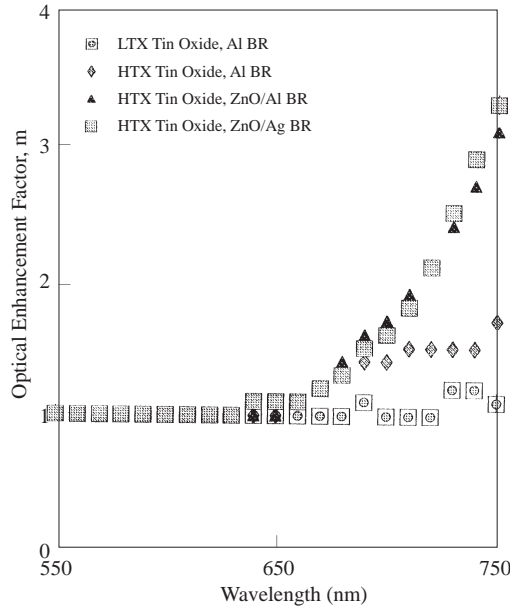


Figure 4. Optical enhancement factor m versus wavelength for solar cells with all four combinations of SnO₂ and BR.

Figures 5 and 6 illustrate the calculated i-layer absorbance A_i and the enhancement $f(R_B)$ (due to the back reflection) versus wavelength for all 4 cells used here. In both figures, the advantages of using HTX SnO₂ and the ZnO/metal (Al or Ag) BR are clearly seen at the higher wavelengths (650-750 nm) where the optical enhancement occurs as expected.

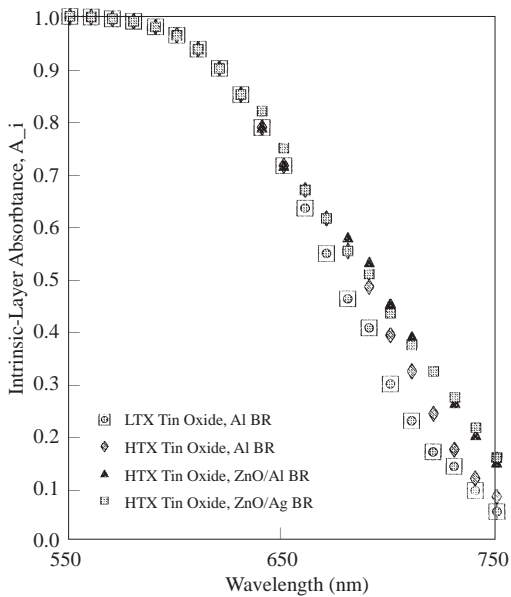


Figure 5. Calculated intrinsic (i-) layer absorbance A_i versus wavelength for solar cells with all four combinations of SnO₂ and BR.

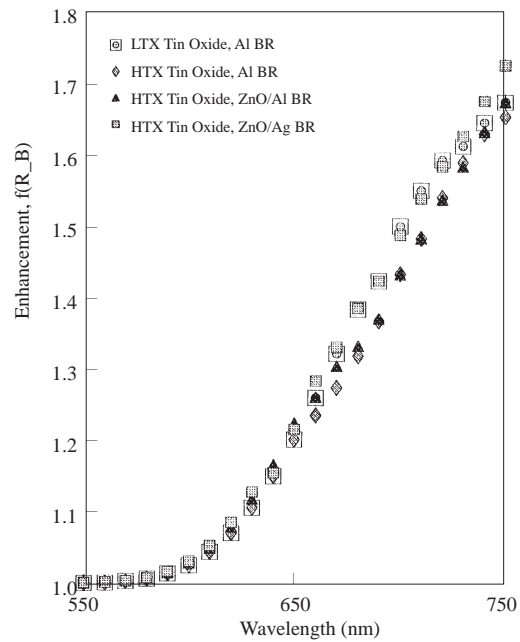


Figure 6. Calculated $f(R_B)$ versus wavelength for solar cells with all four combinations of SnO₂ and BR.

5. Conclusion

A simple optical model was applied to analyze the measured QE of four a-Si:H p-i-n solar cell devices deposited on LTX and HTX SnO₂ substrates with three types of BR. The parameter m quantifies the optical enhancement by representing the extra average length for light at each wavelength before is absorbed in the i-layer of cell. The maximum values of $m \sim 1.5, 3$ and 4 were found for BR of Al, ZnO/Al or ZnO/Ag, respectively. These results imply the importance of increasing the reflectivity of the BR in order to increase light trapping, by increasing the number of additional passes the light can make without being absorbed.

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