

# Optical Design and Analysis of Textured a-Si Solar Cells

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# OPTICAL DESIGN AND ANALYSIS OF TEXTURED A-SI SOLAR CELLS

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## ABSTRACT

The effect of texture on enhancement and losses in photocurrent in a-Si solar cells is explored using PVOPTICS software and measurements on a-Si device structures. The texture angle has a major impact on light trapping and internal reflection. Increasing the angle causes better internal trapping in the i-layer, but also higher SnO<sub>2</sub>/a-Si reflection losses, as well as SnO<sub>2</sub> and metal absorption losses. Parasitic absorption in the textured SnO<sub>2</sub> due to back reflected light is 1-2 mA/cm<sup>2</sup> for typical designs. N-i-p cells have a fundamental advantage over p-i-n cells since the textured TCO is at the rear of the device leading to lower losses.

## INTRODUCTION

Optical analysis of a-Si devices on textured substrates can be very complicated due to multiple reflections and scattering at oblique angles (see Fig. 1). While photocurrent ( $J_{PH}$ ) and quantum efficiency (QE) increase with texture due to beneficial light trapping, parasitic absorption losses also increase. The enhancement in QE has been successfully analyzed using simple models which determine the increase in optical path length [1,2], but identifying where losses occur is more difficult. Unexplained losses at longer wavelengths are usually attributed to parasitic absorption at the back contact, but some groups [1,3] have speculated that these losses are due to light which is trapped and absorbed in the textured SnO<sub>2</sub> after being reflected from the back contact. Further insight into the relation between the SnO<sub>2</sub> texture and the photocurrent requires numerical modeling. For a more complete discussion of a-Si optical models, see Ref. 1.

## ANALYSIS USING PVOPTICS

We have undertaken a study of optical losses and enhancement in a-Si devices on textured SnO<sub>2</sub> substrates using PVOPTICS, a software package developed at NREL for Si solar cells including a-Si [4,5]. PVOPTICS can analyze smooth or textured multilayer thin film structures where the film thickness and texture size are comparable to the wavelength. It combines ray and wave optics using coherence as the selection criteria.

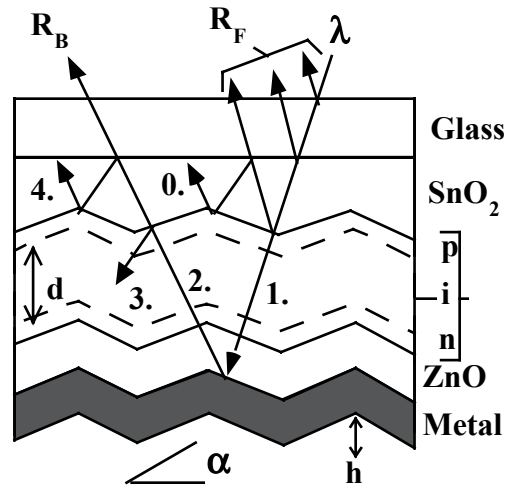


Fig. 1. Device structure which was analyzed using PVOPTICS with rays 0-4 discussed in text.

PVOPTICS allows the texture to be specified in terms of an angle ( $\alpha$ ) from the horizontal and height ( $h$ ) (see Fig. 1). It includes parameters for modeling realistic devices including the SiO AR coating between the glass and SnO<sub>2</sub>, and the dielectric (ZnO) buffer layer commonly used in high performance ZnO/Al or ZnO/Ag back reflectors (BR). Absorption losses in the metal or buffer/metal BR have been studied using PVOPTICS [5]. It was crucial for this work to obtain accurate optical constants of commercially available textured SnO<sub>2</sub> films. They were determined using Variable Angle Spectroscopic Ellipsometry (VASE). Determining correct VASE measurement procedures and selection of a correct model for textured SnO<sub>2</sub> films is non-trivial. A detailed description of the procedure used here, which involved VASE measurements on polished SnO<sub>2</sub> samples, is in preparation.

PVOPTICS quantifies the optical absorption of each layer by converting it to an effective AM1.5 photocurrent calculated over a specified wavelength region (400-800 nm was used here). Figure 2 shows the good agreement between the measured photocurrent  $J_{PH}$  obtained from integrating the spectral response at reverse bias with the AM1.5 spectrum and the calculated  $J_{PH}$  for a series of p-i-n devices with i-layer

thicknesses from 0.16 to 0.9  $\mu\text{m}$ . They were deposited on lightly textured (LTX) LOF Tec10 ( $h=0.05 \mu\text{m}$ ,  $\alpha=10^\circ$ ) and highly textured (HTX) Asahi Type U ( $h=0.1 \mu\text{m}$ ,  $\alpha=30^\circ$ )  $\text{SnO}_2$  substrates. The  $\text{SnO}_2$  texture was obtained from SEM cross section and TEM [6]. Devices had either an Al or ZnO/Ag BR. Here, the thin ZnO buffer layer was represented in PVOPTICS with  $n=2$  and  $k=0$ . A realistic device structure was modeled including the 70 nm SiO layer between the glass and  $\text{SnO}_2$ , and 15 nm p layers. Details on the fabrication, optical properties and QE analysis of these devices can be found in Ref. 1. Generally speaking, increasing the texture from LTX to HTX increased the  $J_{\text{PH}}$  by  $\sim 1\text{mA}/\text{cm}^2$ , and replacing the Al BR with ZnO/Ag increased  $J_{\text{PH}}$  by another  $\sim 1\text{mA}/\text{cm}^2$ . PVOPTICS predicts the correct trends with thickness, texture and back contact reflectivity, and has good quantitative agreement with measured  $J_{\text{PH}}$ . This verifies using PVOPTICS for characterizing a-Si solar cells. In the following discussion, we use a simplified device structure consisting of glass( $k=0$ )/0.5  $\mu\text{m}$   $\text{SnO}_2$ /0.4  $\mu\text{m}$  a-Si/0.1  $\mu\text{m}$  ZnO/Al to focus on the textured  $\text{SnO}_2$  and i-layer absorption using a standard BR.

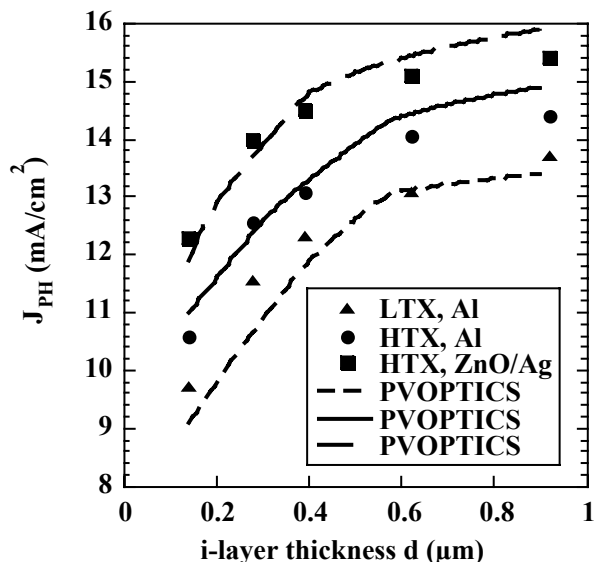


Fig. 2. i-layer thickness dependence of  $J_{\text{PH}}$  for p-i-n cells on LTX and HTX  $\text{SnO}_2$  with Al or ZnO/Ag back reflectors. Lines calculated by PVOPTICS.

### Effect of texture angle and height

Figure 3 shows the dependence on the texture angle with  $h=0.1 \mu\text{m}$  of the equivalent current absorbed in the front textured  $\text{SnO}_2$ , the i-layer ( $J_{\text{PH}}$ ), and the metal, compared to the specular case ( $h=\alpha=0$ ). There is a significant increase in all absorption for  $\alpha>10^\circ$  and a decrease near  $45^\circ$ .  $\text{SnO}_2$  and metal absorption losses are comparable. Figure 4 shows the calculated total reflection  $R$  for 4 different angles where  $R=R_{\text{F}}+R_{\text{B}}$  (see Fig. 1). For wavelengths less than 600 nm,  $R$  is due to air/glass, glass/ $\text{SnO}_2$ , and textured  $\text{SnO}_2$ /a-Si

interfaces ( $R_{\text{F}}$ ). Beyond 600 nm there is also a contribution from light reflected at the BR ( $R_{\text{B}}$ ), but not trapped within the structure. For the specular case,  $R$  is high at all wavelengths. For  $\alpha=10^\circ$ , there is a slight decrease in  $R$  at long wavelengths compared to the specular case signifying some light trapping of weakly absorbed photons (lower  $R_{\text{B}}$ ). There is a rapid increase in  $J_{\text{PH}}$  for angles above  $10^\circ$ . Figure 4 shows that this coincides with a decrease in  $R$  at all wavelengths. This is a well established feature of texturing [7] and is due to both reduced front surface  $R$  and increased light trapping. However, an unusual effect occurs at  $45^\circ$  texture. Figure 3 shows that absorption in all three portions of the device ( $\text{SnO}_2$ , i-layer, and BR) decreases. It is unusual for the losses and the photocurrent to all simultaneously increase then decrease. Figure 4 shows that for  $45^\circ$ ,  $R$  increases in the blue ( $R_{\text{F}}$ ), but decreases in the red ( $R_{\text{B}}$ ) compared to  $20^\circ$ , which is understood as follows, referring to Figure 1. As the angle between the interface and the incident light increases, the reflection of light incident from either side increases. Therefore, with increasing  $\alpha$ , the  $R$  for incident light at the  $\text{SnO}_2$ /a-Si increases, resulting in less light entering the a-Si and higher  $R_{\text{F}}$ . But red light inside the device which is reflected at the BR and passes through the i-layer again without being absorbed (ray 2), will experience a higher internal  $R$  at the  $\text{SnO}_2$ /a-Si, thus reflecting a higher fraction back into the i-layer for a third pass (ray 3). This results in lower  $R_{\text{B}}$ .

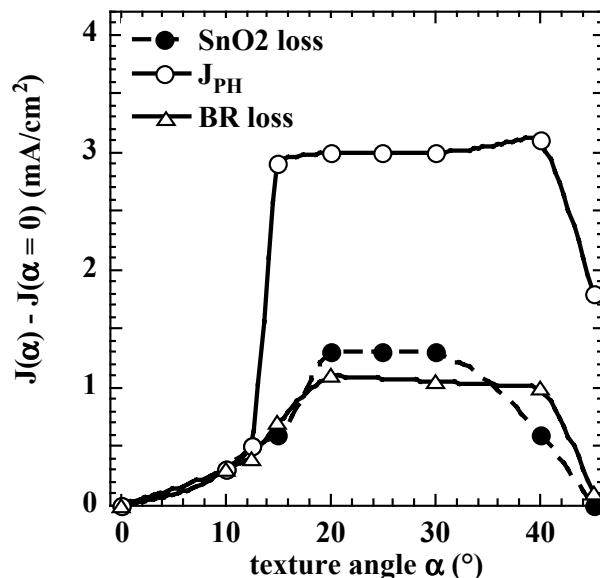


Fig. 3. Calculated effect of texture angle on photocurrent and absorption losses in  $\text{SnO}_2$  and BR. Specular case absorption:  $\text{SnO}_2=2.0$ ,  $J_{\text{PH}}=12.2$ ,  $\text{BR}=2.2 \text{mA}/\text{cm}^2$ .

We note that the trends in Figure 3 are sensitive to  $\text{SnO}_2$  thickness and BR structure with some cases giving a bimodal distribution of maximum  $J_{\text{PH}}$  with angle.

Clearly, this is a highly coupled system and great care must be taken in determining the impact of one feature on the overall response.

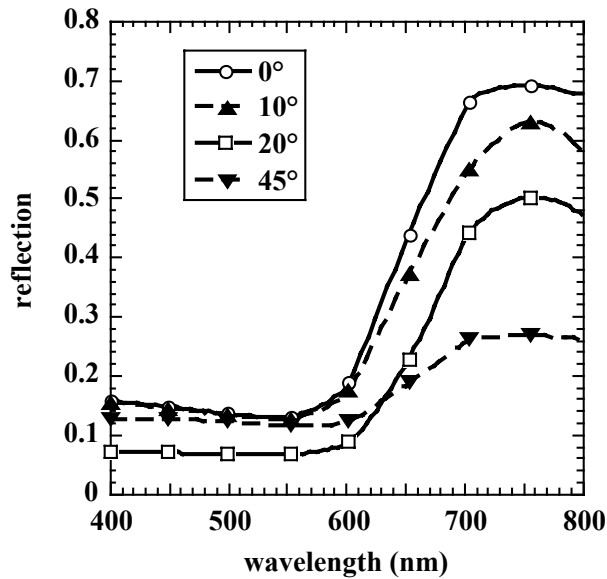


Fig. 4. Calculated reflection spectra for specular and 3 texture angles for  $\alpha$  devices from Fig. 3.

The effect of increasing  $h$  was investigated at several fixed values of  $\alpha$ . There is a significant increase in  $J_{PH}$  (2-4 mA/cm<sup>2</sup>) with  $h=0.02$   $\mu$ m compared to the specular. There was little change after that as  $h$  increased to 0.3  $\mu$ m. Thus, light trapping is more sensitive to  $\alpha$  than  $h$ .

#### Effect of texture on parasitic SnO<sub>2</sub> absorption due to light trapping

Simulations were made to calculate the contribution of first pass vs back reflected light on absorption in the SnO<sub>2</sub>. First pass light represents only light which is absorbed as it initially enters the SnO<sub>2</sub> from the glass, and may be a single pass in the case of specular, or multiple pass if it is internally reflected in the textured SnO<sub>2</sub> (ray 0 in Fig. 1). Back reflected light in the SnO<sub>2</sub> has been reflected at the BR but not absorbed in its second pass through the i-layer (ray 4). The structure was glass/0.5  $\mu$ m SnO<sub>2</sub>/0.4  $\mu$ m i-layer/ZnO/Ag. First pass SnO<sub>2</sub> absorption was calculated with PVOPTICS by using a very thick low band gap a-SiGe i-layer so that no light in the range 400-800 nm reaches the BR, hence there was no rays 2, 3 or 4. Table 1 shows the absorption in the three regions for 0, 30, or 45° and  $d=\infty$  and 0.4  $\mu$ m. The first line indicates the specular Asahi SnO<sub>2</sub> would absorb only ~2 mA/cm<sup>2</sup> if light were to pass through once without any multiple reflections. We found that texturing the SnO<sub>2</sub> ( $\alpha=30$  and 45°) results in a negligibly small change in absorption for first pass light. However, when back reflected light (ray 4) is allowed to enter the SnO<sub>2</sub> by having a thinner a-Si i-layer, the

absorption in the SnO<sub>2</sub> increases. At 30°, it increases by 1.5 mA/cm<sup>2</sup>, which is 10% of the total  $J_{PH}$ . The increase is larger for  $\alpha=30^\circ$  compared to  $\alpha=45^\circ$  consistent with arguments in the previous section. Comparing 30 to 45°, the SnO<sub>2</sub> and metal losses are higher, but  $J_{PH}$  is also higher. Table 1 shows that back reflected light can result in ~1.5 mA/cm<sup>2</sup> additional absorption in the SnO<sub>2</sub>. This represents light which has made at least 2 passes through the i-layer, but was not absorbed. The back reflected SnO<sub>2</sub> absorption is comparable to the first pass absorption (2.0 mA/cm<sup>2</sup>). We suggest that absorption in the SnO<sub>2</sub> due to back reflected light is the source of the unexplained losses mentioned in the introduction. This loss increases as the wavelength region under consideration increases as for low bandgap a-SiGe devices.

Table 1. Calculated absorption in the SnO<sub>2</sub>, i-layer ( $J_{PH}$ ), and metal layer for a p-i-n device structure of Fig. 1 for different  $\alpha$  and  $d$ . "Infinite" thickness corresponds to 10  $\mu$ m a-SiGe layer to prevent any back reflection so that SnO<sub>2</sub> loss corresponds to only first pass light.

Angle $\alpha^\circ$	$d$ ( $\mu$ m)	SnO <sub>2</sub> (mA/cm <sup>2</sup> )	$J_{PH}$ (mA/cm <sup>2</sup> )	metal (mA/cm <sup>2</sup> )
0-45	$\infty$	1.9-2.0	X	0
0	0.4	2.0	12.2	2.2
30	0.4	3.4	15.2	2.9
45	0.4	2.0	14.0	2.3

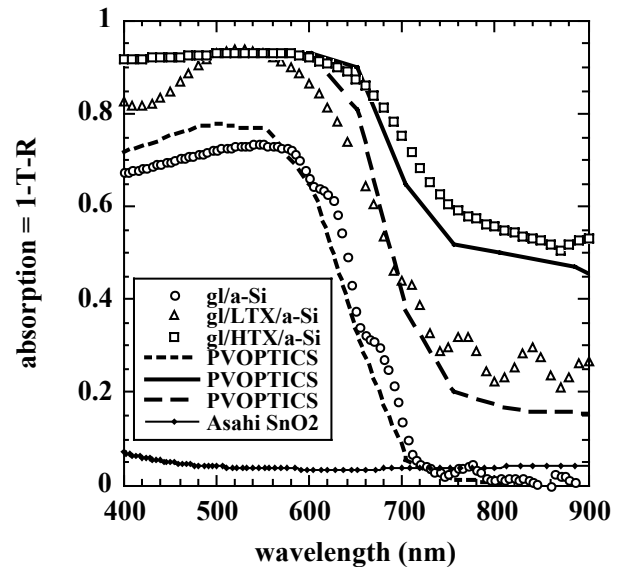


Fig. 5. Measured and calculated absorption for 0.5  $\mu$ m a-Si film on various glass (gl)/textured SnO<sub>2</sub> substrates. Absorption of Asahi (HTX) SnO<sub>2</sub> from VASE also shown.

To further study this effect, simple structures were fabricated by depositing 0.5  $\mu$ m a-Si layers on smooth glass and on the LTX and HTX types of SnO<sub>2</sub>. No BR

was applied. Reflection R and transmission T were measured and absorption was determined from 1-T-R. The effect of absorption in the textured SnO<sub>2</sub> is clearly seen in Figure 5. The a-Si absorption is near zero beyond 700 nm on smooth glass, but the absorption of the LTX SnO<sub>2</sub>/a-Si is ~0.20 and the HTX SnO<sub>2</sub>/a-Si is ~0.5. The absorption of the SnO<sub>2</sub> is < 0.05 for a single pass in this range. Clearly, the increased absorption must be due to light trapped in the SnO<sub>2</sub>, not a-Si. PVOPTICS matches the measured data fairly well. Note that in the range of interest for maximizing red response of a-Si/a-SiGe multijunctions, (700-900 nm) the absorption in the Asahi HTX SnO<sub>2</sub> due to multiple passes is 50% which is quite substantial.

### Comparing n-i-p and p-i-n devices

The a-Si photovoltaic field has evolved with p-i-n and n-i-p device structures each having unique advantages for manufacturing. Both n-i-p and p-i-n devices utilize light trapping by depositing the a-Si layers on a textured transparent conductive oxide TCO substrate, typically SnO<sub>2</sub> for the p-i-n and ZnO for n-i-p cells. Differences in their optical performance are related to the fact that light for the p-i-n device enters through the 0.5-1.0 μm thick textured TCO while light for the n-i-p enters through a much thinner 0.07 μm TCO layer, which serves as an AR coating as well as conductive contact. In the n-i-p device, light does not enter the thick textured TCO layer until it has passed through the a-Si layers.

We have modeled simple p-i-n and n-i-p devices using PVOPTICS. The same layers and parameters (h=0.1, α=30°) were used for each. Only the order was changed, with light always entering SnO<sub>2</sub>(1) before the i-layer and SnO<sub>2</sub>(2) after the i-layer. The cell structure was: encapsulant (n=1.5, k=0)/ SnO<sub>2</sub>(1)/a-Si(0.4 μm)/ SnO<sub>2</sub>(2)/Al. For the p-i-n device, SnO<sub>2</sub>(1) was 0.5 μm and SnO<sub>2</sub>(2) was 0.07 μm. For the n-i-p device, SnO<sub>2</sub>(1) was 0.07 μm and SnO<sub>2</sub>(2) was 0.5 μm.

Table 2. Current in mA/cm<sup>2</sup> absorbed in the first and second TCO layers and i-layer of p-i-n and n-i-p devices with symmetrical structure. The metal absorption was ~2.7 mA/cm<sup>2</sup> for each.

device	SnO <sub>2</sub> (1)	J <sub>PH</sub> (i)	SnO <sub>2</sub> (2)
→p-i-n	1.9	16.0	0.1
n-i-p←	0.2	17.1	0.9

Table 2 shows that the n-i-p cell has ~1 mA/cm<sup>2</sup> higher photocurrent, due to having ~1 mA/cm<sup>2</sup> less absorption losses in the two layers compared to the p-i-n cell. Metal absorption was similar for both since it depends on the angle and the optical constants of the materials used for the BR (SnO<sub>2</sub>/Al). Thus, the main optical advantage of the n-i-p is lower absorption in the front TCO layer. However, this is partially offset by a 3% grid shadowing loss typically found in the n-i-p device (not included here).

We also compared a-Si/a-SiGe tandem devices in the p-i-n and n-i-p configuration, and arrived at the same conclusions. Additionally, the lower SnO<sub>2</sub>(1) absorption for the n-i-p allowed both i-layers of the tandem to be made thinner while producing the same photocurrent compared to the p-i-n.

### CONCLUSIONS

Light trapping in even simplified device structures with textured interfaces can be very complex. The angle of texture can have competing influences which can lead to increases or decreases in J<sub>PH</sub> depending on other design parameters. Increasing the angle of the texture results in less reflection losses and better light trapping, hence higher photocurrents, but also larger parasitic absorption losses in the SnO<sub>2</sub> and metal BR. Parasitic absorption in the textured SnO<sub>2</sub> due to back reflected light is 1-2 mA/cm<sup>2</sup>. N-i-p cells have a fundamental advantage over p-i-n cells since their thick textured TCO layer is at the back rather than the front of the cell where the light intensity is lower.

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