Textured Thin-film Solar Cell Simulation

Texturing is often used to improve light trapping in thin film solar cells. The textured surfaces act to scatter the light in oblique angles lengthening the optical path and effectively trapping a greater percentage of light within the thin layers.

Numerical simulation including self-consistent inclusion of optical and electrical simulation has been an important tool in optimization of solar cell designs. However texturing is problematic for numerical optoelectronic simulation of thin film solar cells. Purely geometric simulation such as Ray Tracing Method (RTM) is not suitable since it ignores interference effects occurring in devices with material layers with thicknesses on the order of the wavelength of the incident light. Also it is difficult to properly describe randomly textured surfaces geometrically. On the other hand coherent modeling using Transfer Matrix Methods (TMM) ignores the effects of surface texturing. Finite difference time methods could also be used but at an enormous sacrifice in computation time and with problems with periodicity and non-normal incidence.

An approach that accounts for both the coherent propagation of specular light as well as the diffuse propagation of incoherent light occurring at the rough interfaces in the device has been proposed (1,2,3). In this approach, coherent light is modeled using the transfer matrix method while incoherent light is modeled using geometric methods. This model is incorporated into the Luminous simulator in the ATLAS framework for self consistent optical propagation and drift-diffusion simulation of photo-detection problems.

The relation between coherent and incoherent light is defined by a set of haze functions defined at each textured interface. The haze functions $H_T$ and $H_R$ as illustrated in Figure 1, define the ratio of transmitted diffuse intensity to the specular incident intensity and the ratio of the reflected diffuse intensity to the specular incident intensity.

The haze functions are calculated by the expressions:

$$H_T = 1 - \exp\left[-\frac{4\pi \text{SIGMA} \cdot CT \cdot |n_1 - n_2|}{\lambda} \right]^{NT}$$  (1)

$$H_R = 1 - \exp\left[-\frac{4\pi \text{SIGMA} \cdot CR \cdot n_1}{\lambda} \right]^{NR}$$  (2)

where $\lambda$ is the optical wavelength, CT, CR, NT, NR and SIGMA are user definable model parameters. The parameter SIGMA is a measure of the mean feature size at the interface. The default values of the model parameters are given in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
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<tr>
<td>CR</td>
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<tr>
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Table 1. Default parameter values for the haze functions.

Figure 2 shows example calculations of the haze functions versus wavelength for various values of SIGMA. The diffuse light is reflected and transmitted in random directions from the interface. The distribution of diffuse light can be described by an angular distribution function, ADF. The ATLAS-Luminous simulator supports several user selectable ADFs as summarized in Table 2.

In Table 2, $\phi$ is the angle of propagation with respect to the normal to the interface and the ADFs are un-normalized. Normalization insures conservation of intensity derived from the haze functions above.
The geometrical contribution of the diffuse light is accounted for in the calculated photogeneration rate given in equation 3 where $P_o$ is the intensity at the interface, $y$ is the distance normal to the interface and $\alpha$ is the absorption coefficient.

$$G(y) = 2 \int_0^{\pi/2} P_o \text{ADF}(\phi) \frac{-\alpha y}{\cos \phi} d\phi$$  \hspace{1cm} (3)

Reflection and refraction of diffuse light at subsequent interfaces is modeled using the Fresnel equations.

As a comparison we preformed an experiment as described in reference 4. The device is a CuInGaSe$_2$ solar as described in Figure 3.

For this simulation we combined the top two ZnO layers from reference 4 into one layer since we did not know how the authors handled these layers. The top three interfaces were modeled as rough interfaces. We ignored the effect of the back side glass since we had no information about its composition.

We digitized the complex index data for the CdS and CIGS layers from the reference. We used our built-in index data for the ZnO and Mo layers since we did not know what the authors used. For the tuning parameters we used the values in Table 1 to match the parameter values used in reference 4. We also chose to use an elliptical ADF with a semi-minor axis of 0.31 as suggested in the reference. A comparison of our simulation to the experimental results in reference 4 are shown in Figure 4.

**Table 2.** Un-normalized Angular Distribution Functions in Luminous.

| CONSTANT: ADF(\phi) = 1 |
| TRIANGLE: ADF(\phi) = 1 - 2\phi/\pi |
| GAUSS: ADF(\phi) = \exp\left(-\frac{\phi^2}{2\text{DISPERSION}}\right) |
| LORENE: ADF(\phi) = \exp\left(-\frac{1}{\phi^2 + \text{DISPERSION}^2}\right) |
| LAMBERT: ADF(\phi) = \cos(\phi) |
| ELLIPSE: ADF(\phi) = \frac{\cos(\phi)}{\cos^2(\phi) + \left(\frac{0.5}{\text{SEMINOR}}\right)^2 \sin^2\phi} |

**Figure 2.** Example haze functions as a function of wavelength for various SIGMA.

**Figure 3.** Experimental CuInGaSe$_2$ Solar Cell.
Here we see good agreement between experiment and simulation.

The simulated results for TMM only as well as RTM only are also shown in Figure 5. This underscores the necessity of inclusion of diffusive interfaces as well as the effect of interferences for textured devices.

In the second example from reference 1, we simulated a thin film hydrogenated amorphous silicon cell. The device consists of a one half micron thick textured transparent conducting oxide, on top of p/i/n textured layers of amorphous silicon of thicknesses 9nm/650nm/20nm all on top of 300 nm of silver, shown in figure 6. Figure 7 shows excellent comparison between experiment and simulation for this device.

**Conclusion**

We have implemented a self-consistent optoelectronic model for simulation of solar cells with rough textured interfaces. This simulator combines simulation of specular and diffuse light with haze functions describing the relation between the light intensities and angular distribution functions describing the diffuse dispersion of light. The comparison with experiment gives good accuracy.

**References**


(5) Krc, J., Zeman, M.