Introduction

The TAG compact model describes the physics of p-i-n thin film cells for use in panel level simulation. It is aimed at enabling photovoltaic system simulations to understand the roles of variability and reliability on the performance of solar modules. In this brief manual, we discuss the general features of this model as well as the parameter extraction procedures and details of a panel circuit builder. For additional information about this model and its application to panel level simulation, see Ref. [1].

The term, TAG, is an abbreviation of the phrase “technology agnostic.” This model is part of a larger effort at Purdue University to develop a suite compact models for various solar cell technologies. Each model shares common, physics-based elements, but each one is tuned to the specific technology being modeled – in this case, amorphous silicon.

2. Verilog-A Implementation

2.1 Definition of Terminal Voltage

As shown in Figure 1, the external terminals are labeled as vp (anode) and vn (cathode). The internal terminal labelled as vpi is separated from external terminal by the resistor, $R_s$, which represents the series resistance of the transparent conductive oxide layer.

![Fig. 1 Equivalent circuit incorporating the intrinsic components (orange box) and extrinsic components (blue box).](image-url)
Voltage definitions:

\[ V_{i} = V(v_{pi}, v_{n}) \]
\[ V_{re} = V(v_{p}, v_{pi}) \]

2.2 Parameter List

The parameters used in the TAG solar cell model are listed as below. The physical meanings of each of the parameters will be explained as below.

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real</td>
<td>area</td>
<td>active cell area [m²]</td>
</tr>
<tr>
<td>Real</td>
<td>jphoto_max</td>
<td>maximum photocurrent [A/m²]</td>
</tr>
<tr>
<td>Real</td>
<td>j0_diode</td>
<td>diode saturation current [A/m²]</td>
</tr>
<tr>
<td>Real</td>
<td>n_fac</td>
<td>ideality factor</td>
</tr>
<tr>
<td>Real</td>
<td>vbi</td>
<td>built-in voltage [V]</td>
</tr>
<tr>
<td>Real</td>
<td>abs_diff</td>
<td>ratio between absorber thickness and diffusion length</td>
</tr>
<tr>
<td>Real</td>
<td>gsh1</td>
<td>shunt conductance parameter 1 [S/m²]</td>
</tr>
<tr>
<td>Real</td>
<td>gsh2</td>
<td>shunt conductance parameter 2 [S/m²]</td>
</tr>
<tr>
<td>Real</td>
<td>n_sh</td>
<td>shunt conductance voltage index</td>
</tr>
<tr>
<td>Real</td>
<td>rsheet</td>
<td>sheet resistance [Ohms]</td>
</tr>
<tr>
<td>Real</td>
<td>smooth_p</td>
<td>smooth parameter for a step function</td>
</tr>
</tbody>
</table>

The thermal voltage, \( V_T \), is available within the Verilog-A code. It is a constant parameter that can be accessed in Verilog-A with the notation “\$vt”.

2.3 Intrinsic Current Components

It is common to model solar cells using the superposition principle: the current under illumination at a voltage, \( V \), is the sum of the current in the dark at voltage, \( V \), and the short circuit current under illumination [2]. We write the current as

\[ J(V, G_{op}) = J_D(V) - J_{SC}(G_{op}). \]  (1)

where, \( J_D(V) \) is the dark current and \( J_{SC}(G_{op}) \) is the short circuit current. The photocurrent of c-Si cells is adequately described by the superposition principle. Thin-film solar cells are often more complicated. In general, we can describe their IV characteristics under illumination by

\[ J(V, G_{op}) = J_{inj}(V, G_{op}) - J_{photo}(V, G_{op}). \]  (2)
The diode injection current, \( J_{\text{inj}}(V, G_{\text{op}}) \), depends, in general, on both the applied voltage and on the optical generation, and may differ from \( J_D(V) \) due to the generation dependent recombination current, see in Figure 1. The photocurrent, \( J_{\text{photo}}(V, G_{\text{op}}) \), depends, in general, on both the optical generation and on the applied voltage and may differ from \( J_{\text{SC}}(G_{\text{op}}) \). To model thin-film solar cells, we must model these effects.

### 2.3.1 Diode dark current

By solving the drift and diffusion equations analytically in the absence of bulk recombination, we can solve for the dark current of a p-i-n diode. This current component has an ideality factor of one (the result is the so-called ideal diode equation). The voltage applied across a p-i-n diode drops mostly across the i-layer. Moreover, the recombination in this constant field region gives additional current component. The generation-independent part of this recombination current has an ideality factor of two. For simplicity, in the model, we combine these two current components and describe them by the empirical formula below.

\[
J_{\text{diode}}(V_i) = j0_{\text{diode}} \times (\exp(V_i/V_T/n_{\text{fac}}) - 1).
\]  

(3)

The ideality factor, \( n_{\text{fac}} \), here is a parameter between 1 and 2. In general, it varies with bias, but is treated as a constant in the model.

### 2.3.2 Generation-dependent recombination current

As indicated in Figure 1, the diode injection current, \( J_{\text{inj}}(V, G_{\text{op}}) \), depends on both voltage and photogeneration. In the model, we describe the injection current as the sum of two terms. The first is the dark current discussed in Sec. 2.3.1, and the second in a generation-dependent diode injection current. As discussed in the appendix of [1], the part that depends on photogeneration gives a generation-dependent recombination current as

\[
J_{\text{rec,G}} = \text{smooth}_\text{rec} \times j_{\text{photo,max}} \times \text{abs}_\text{diff}^2 \times V_T / (vbi - V_i) / 4,
\]  

(4)

where the first term, \( \text{smooth}_\text{rec} \), is the continuous "step function" described by

\[
\text{smooth}_\text{rec} = 0.5 \times \left(1 - \tanh(\text{smooth}_p \times (V - 0.95 \times vbi)))\right),
\]  

(5)
The rest of the terms are defined in Sec. 2.2. The purpose of the step function is to account for the fact that the treatment of charge partitioning by (4) is only valid when \( V_i \) is less than \( vbi \). As a consequence, \( J_{rec} \) is set to be zero when \( V_i \) is greater than 0.95 \( vbi \). The use of a smooth step function ensures that the expressions give well-behaved derivatives, which are necessary for numerical convergence. Note that \textit{smooth}.\textit{p} is not a fitting parameter; it is set to be sufficient large \( 10^5 \) to ensure that the step function is sharp.

2.3.3 Photocurrent

Just as an expression for the generation-independent diode injection current can be analytically derived (i.e. eqn. (3)), an expression for bias-dependent photo-current can also be derived. The result is

\[
J_{\text{photo}} = j_{\text{photo max}} \times \left( \coth \left( \frac{q(V_i - vbi)}{2RT} \right) - \frac{2VT}{(V_i - vbi)} \right). \tag{6}
\]

This expression claims a discontinuity at \( V_i = vbi \). Taking the limit as \( V_i \) approaches \( vbi \) from either the positive or negative direction, we find that \( J_{\text{photo}} (V = vbi) \) equals zero. Thus, \( J_{\text{photo}} \) is set to be zero at \( V_i = vbi \), which maintains the continuity of \( J_{\text{photo}} \) in the Verilog-A code.

2.4 Parasitic Components

2.4.1 Parasitic Shunt Current

The shunt current model consists of two parts. The first one describes the usual ohmic shunt conductance, and the second is Space-Charge-Limited (SCL) current transport, which has a non-ohmic characteristic. The semi-empirical formula used in the model is [3]

\[
J_{\text{shunt}} = gsh1 \times V_i + gsh2 \times \tanh \left( \text{smooth} \times p \times V_i \right) \times \text{abs} \left( V_i \right)^{nsh}. \tag{7}
\]

The parameters, \( gsh1 \) and \( gsh2 \), describe the ohmic and non-ohmic shunt components, respectively. The \( nsh \) parameter is an exponent index with a typical range of 2 to 3, characteristic of SCL transport. The \( \tanh(\bullet) \) function in (7) provides the sign of \( V_i \) and also keeps the expression continuous.

2.4.2 External Sheet Resistance

The second important parasitic component in solar cells is the external sheet resistance, which arises from the contact layer, because the current must
flow a certain distance before reaching the terminals. The finite resistance of the contact layers then causes extra output power loss. For simplicity, we use a single parameter, \( r_{\text{sheet}} \), to describe the distributed sheet resistance. The sheet resistance is often higher at the module level, because it arises from the lateral current flow in metal/TCO layers. As a result, it should be noted that the value of \( r_{\text{sheet}} \) cannot be determined by fitting the IV characteristic of a single cell. The details of the physics are explained in Chapter 4 of [1].

**Note:**
The derivation of the formulas used in this model as listed above can be found in the appendices of [1].

3. Parameter Extraction

The purpose of Sec. 3 is to provide instructions to extract TAG model parameters from experimental or simulated data. This section is divided into two parts: dark IV and illuminated IV characteristics.

3.1 Dark IV:

**Extracted Parameter list (dark IV):** \( j_0_{\text{diode}}, n_{\text{fac}}, gsh1, gsh2, \text{ and } n_{\text{sh}}. \)

A typical dark IV characteristic is shown in Figure 2. [4] Under low forward and reverse biases, the total current is dominated by the shunt current described by eqn. (7). The shunt current consists of two parallel components and can be described by

\[
J_{\text{shunt}} = gsh1 \times V + gsh2 \times \text{sign}(V) \times |V|^{n_{\text{sh}}}. \tag{8}
\]

The two parameters, \( gsh1, gsh2 \), and the shunt power exponent index, \( n_{\text{sh}} \) can be determined by fitting (7) to the reverse bias data. Please note that it is NOT recommended to fit the shunt current just using the low reverse bias current, such as from -0.2 V to -0.1 V. It will cause troubles later on due to the poor accuracy of the shunt conductance. The recommended voltage range to fit the shunt current is in the reverse bias from -1 V to 0 V in most cases. The fitting process can be achieved by the least square fitting function, “lsqcurvefit”, in Matlab or a tool named “PVanalyser” [4] on PVhub (http://nanohub.org/pvhub).
After obtaining the parameters for the shunt conductance, we can proceed to “clean” the dark IV to extract for dark diode parameters. The voltage symmetry of the shunt current (i.e. $J_{Shunt}(-V) = J_{Shunt}(V)$) offers an easy method to separate the shunt and diode current components. Notice that the reverse current of the cell in Figure 2 is dominated by the shunt current. Thus, the forward diode current can be obtained simply by subtracting the reverse current from the forward current [4]. A comparison of original data and “cleaned” data is shown in Figure 3 [4].

By fitting the “cleaned” IV data to the diode equation with series resistance,

$$J_D = J_0 \exp \left( \frac{q(V - I_D R_{Series})}{n \times kT} \right)$$

we obtain the diode saturation current, $J_0$ ($j0\_diode$), the ideality factor, $n$ ($n\_fac$), and the series resistance, $R_{Series}$. The series resistance, $R_{Series}$, obtained by this process is not the sheet resistance ($r_{sheet}$) in this model (the sheet resistance in the module level is usually higher than the series resistance of a single cell). Similar to fit the shunt current, the fitting procedure can be done using either Matlab or “PVanalyzer” [4].
3.2 Illuminated IV

Extracted Parameter list (light IV): \( v_{bi} \), \( j_{photo\_max} \), and \( abs\_diff \).

For a p-i-n thin film solar cell, it is commonly observed that the dark and light IV characteristics cross-over each other under forward bias. This is typically due to a voltage-dependent photocurrent. The voltage at which the IV characteristics crossover is called the crossover voltage. As discussed in [5], when the voltage dependent photocurrent is due to carrier partitioning, the crossover voltage equals to the built-in voltage of the p-i-n junction. Thus, finding the cross-over voltage of the dark and light IV curves will give the built-in voltage \( (v_{bi}) \).

At strong reverse bias of light IV data, the current is mainly the addition of the shunt current and a bias-independent photocurrent \( (j_{photo\_max}) \). At strong reverse bias voltage around -1 V, by subtracting the dark IV current (shunt current) from the light IV current (shunt current plus photo-generation current), we can deduce the parameter \( j_{photo\_max} \).

If the absorber thickness is known, and if the diffusion length (which depends on carrier mobility and lifetime) is available, then the ratio between absorber thickness and diffusion length \( (abs\_diff) \) can be determined. If neither of the absorber thickness nor the diffusion length is known, \( abs\_diff = 1 \) is a good initial guess to fit the curve.
3.3 Iteration Process

Briefly, the process consists of first fitting the dark IV characteristics to determine the parameters, \( j_0_{\text{diode}}, n_{\text{fac}}, gsh1, gsh2, \) and \( n_{\text{sh}} \). The illuminated IV characteristic is then fit to determine the parameters, \( v_{\text{bi}}, j_{\text{photo \_ max}}, \) and \( abs\_\text{diff} \).

One can use the parameters obtained from Sec. 3.1 and Sec. 3.2 as the initial guesses and tweak them to get the best fit of both light and dark IV curves. First, use the numbers obtained from the above steps as initial guesses then fit the dark IV using a computer-aided least squares fitting technique, such as the Matlab function "lsqcurvefit". Next, use the outputs from the previous step as initial guesses to fit light IV with the same technique. A couple of iterations should suffice to give a well-calibrated parameter set. We may need to sacrifice the fit of dark IV somewhat to fit the illuminated IV accurately, which is the priority.

3.4 Example

Consider an illustrative example of parameter extraction of a solar cell. Both the dark and light IV data have been published in [5], and are included in the model release package. The physical parameters of the sample are listed below. Although the cell efficiency is low, this example illustrates the parameter extraction process.

- Cell area: 0.48 cm\(^2\)
- Open circuit voltage: 0.85V
- Short circuit current: 5.3 mA/cm\(^2\)
- Cell efficiency: 3.3%

The following parameter set has been obtained by fitting the I-V characteristic of the sample.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>area</td>
<td>active cell area [m(^2)]</td>
<td>4.8 x 10(^{-5})</td>
</tr>
<tr>
<td>jphoto_max</td>
<td>maximum photocurrent [A/m(^2)]</td>
<td>56</td>
</tr>
<tr>
<td>j0_diode</td>
<td>diode saturation current [A/m(^2)]</td>
<td>1.1 x 10(^{-5})</td>
</tr>
<tr>
<td>n_fac</td>
<td>ideality factor</td>
<td>2.14</td>
</tr>
<tr>
<td>vbi</td>
<td>built-in voltage [V]</td>
<td>1.27</td>
</tr>
<tr>
<td>abt_diff</td>
<td>absorber thickness /diffusion length ratio</td>
<td>0.1</td>
</tr>
<tr>
<td>gsh1</td>
<td>shunt conductance 1 [S/m(^2)]</td>
<td>6.8 x 10(^{-1})</td>
</tr>
<tr>
<td>gsh2</td>
<td>shunt conductance 2 [S/m(^2)]</td>
<td>2.7 x 10(^{-2})</td>
</tr>
<tr>
<td>n_sh</td>
<td>shunt conductance index</td>
<td>2.14</td>
</tr>
<tr>
<td>R_series</td>
<td>series resistance [Ohms]</td>
<td>2.5</td>
</tr>
</tbody>
</table>
*** $R_{Series}$ here is the series resistance of a single cell, which is different from the sheet resistance, $rsheet$, of a panel. At the module level, $rsheet$ is approximately the sheet resistance of the TCO layers [1], assuming that the resistance from the metal layers can be neglected.

Step 1:
Upload dark IV data to “PVanalyzer” [4] on PVhub, and it outputs the parameters to fit dark IV. See Figure 4 for the result.

Fig. 4 Initial fitted data vs. measured dark IV.
Step 2:
The parameters $j_{\text{photo\_max}}$ and $v_{\text{bi}}$ can be estimated from light IV and dark IV, see Figure 5. The initial guess for $\text{abs\_diff}$ is set to 1, for simplicity. Figure 6 shows the fitting result for light IV.

Fig. 5  Light IV vs. dark IV

Fig. 6  Initial fitted data vs. measured light IV.
Step 3: Use the iteration process mentioned in Sec. 3.3 to fit both dark IV and light IV. After a couple of iterations, the final fit is listed below.

Dark IV fit:

![Dark IV fit graph](image1)

Fig. 7 Fitted data vs. measured dark IV.

Light IV fit:

![Light IV fit graph](image2)

Fig. 8 Fitted data vs. measured light IV.
4. Solar Panel Simulation

4.1 Panel Simulation Builder

In the model release package, a panel simulation builder written in Matlab is included. The name of the script is “Panel_Sim_Builder.m”. This panel simulation builder allows users to customize panel simulations. Based on users’ inputs, it will generate a circuit netlist that incorporates the TAG Verilog-A model file. With the netlist, users can simulate the panel performance using circuit simulators. The details about how to define the 2D circuit network for panel simulation are discussed in [6]. Note the current version of the builder is only compatible with HSPICE. Minor modifications of the netlist file may be required for other versions of SPICE engines. A HSPICE toolkit [download: http://www.cppsim.com/download_hspice_tools.html] available in Matlab is helpful to extract simulation data into Matlab for analysis.

The parameters used in the panel simulation builder are listed as below. The default parameters are taken from [7].

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>nrow</td>
<td>number of cells connected in series</td>
<td>10</td>
</tr>
<tr>
<td>ncol</td>
<td>number of cells connected in parallel</td>
<td>10</td>
</tr>
<tr>
<td>plength</td>
<td>panel length [m]</td>
<td>0.1</td>
</tr>
<tr>
<td>pwidth</td>
<td>panel width [m]</td>
<td>0.1</td>
</tr>
<tr>
<td>p_current</td>
<td>photocurrent [A/m²]</td>
<td>100</td>
</tr>
<tr>
<td>rsheet</td>
<td>sheet resistance [Ohms/☐]</td>
<td>1</td>
</tr>
<tr>
<td>g1_mean</td>
<td>mean of gsh1 for lognormal distribution [S/m²]</td>
<td>10⁻¹</td>
</tr>
<tr>
<td>g2_mean</td>
<td>mean of gsh2 for lognormal distribution [S/m²]</td>
<td>10⁻¹</td>
</tr>
<tr>
<td>g1_variance</td>
<td>variance of gsh1 for lognormal distribution [S/m²²]</td>
<td>0</td>
</tr>
<tr>
<td>g2_variance</td>
<td>variance of gsh2 for lognormal distribution [S/m²²]</td>
<td>0</td>
</tr>
<tr>
<td>shad_col_start</td>
<td>starting column of shaded cells</td>
<td>0</td>
</tr>
<tr>
<td>shad_col_end</td>
<td>end column of shaded cells</td>
<td>0</td>
</tr>
<tr>
<td>shad_row_start</td>
<td>starting row of shaded cells</td>
<td>0</td>
</tr>
<tr>
<td>shad_row_end</td>
<td>end row of shaded cells</td>
<td>0</td>
</tr>
<tr>
<td>sha_percent</td>
<td>shading percentage [%]</td>
<td>0</td>
</tr>
<tr>
<td>vdc_s</td>
<td>starting dc sweep voltage [V]</td>
<td>0</td>
</tr>
<tr>
<td>vdc_e</td>
<td>ending dc sweep voltage [V]</td>
<td>10</td>
</tr>
<tr>
<td>dvdc_e</td>
<td>dc sweep voltage step [V]</td>
<td>0.01</td>
</tr>
<tr>
<td>htemp</td>
<td>temperature [°C]</td>
<td>30</td>
</tr>
</tbody>
</table>

The cell area is calculated by dividing the total area of the panel by the number of cells. There are two important scenarios to consider in the panel simulation builder. One is random shunt variability; the other is partial shading. Both of them will be discussed next.
**Shunt Variability**

As discussed in [6], the shunt conductance of thin film solar cells shows a universal lognormal distribution. Given the mean and variance of $g_{sh1}$ and $g_{sh2}$, the builder generates random numbers following the input distribution. If a uniform shunt distribution is needed, we set the mean a constant number and the variance to zero.

**Partial shading:**

Shading is an important issue in a solar panel. Thus, the builder allows users to change the shading condition of the panel. By changing the parameters $shad\_col\_start$, $shad\_col\_end$, $shad\_row\_start$, and $shad\_row\_end$, users are able to control the number and position of shaded cells. The photocurrent of a shaded cell can be controlled by the parameter, $shad\_percent$, so that $J_{Photo}' = J_{photo} \times (1 - shad\_percent)$.

In the following four examples, we will illustrate the panel simulator for a variety of situations.
4.1 Ideal Case Simulation

The following figures show simulation results for a $10 \times 10$ cells panel without shading effects. The shunt conductance is uniformly distributed and $R_{sheet}$ is set to be the default number in the Verilog-A code. The area of the panel is 100 cm$^2$.

Fig. 9 2D power generation of $10 \times 10$ cells at maximum power bias (unit: mW)

Fig. 10 IV characteristics of the panel
Fig. 11 PV characteristics of the panel
4.2 Shunt Variability Simulation

The following figures show simulation results for a $10 \times 10$ cells panel without shading effects. The shunt shows lognormal distribution of both $gsh1$ and $gsh2$ (mean: $6.66 \times 10^{-1}$ S/m$^2$, variance: $1 \times 10^{-1}$ S/m$^2$). $R_{sheet}$ is set to be the default number in the Verilog-A code. The area of the panel is 100 cm$^2$.

Fig. 12 2D power generation of $10 \times 10$ cells at maximum power bias (unit: mW)
TAG Solar Cell Model (p-i-n thin film)

Fig. 13 IV characteristics of the panel.

Fig. 14 IV characteristics of the panel.
4.3 Partial Shading Simulation (i)

The following figure shows simulation results for a 10 × 10 cells panel, in which 10 × 2 cells are 50% shaded and the shunt is uniformly distributed. $R_{sheet}$ is set to be the default number in the Verilog-A code. The area of the panel is 100 cm$^2$.

Fig. 15 2D power generation of 10 × 10 cells at maximum power bias (unit: mW)
TAG Solar Cell Model (p-i-n thin film)

Fig. 16  IV characteristics of the panel.

Fig. 17  PV characteristics of the panel.
4.4 Partial Shading Simulation (ii)

The following figure shows simulation results for a $10 \times 10$ cells panel, in which $3 \times 5$ cells are 50% shaded and the shunt is uniformly distributed. $R_{sheet}$ is set to be the default number in the Verilog-A code. The area of the panel is 100 cm$^2$.

Fig. 18 2D power generation of $10 \times 10$ cells at maximum power bias (unit: mW)

Fig. 19 IV characteristics of the panel.
Fig. 20 PV characteristics of the panel.

5. Summary

The manual discusses the basic elements of the TAG solar cell model, the parameter extraction procedures, and the panel simulation builder as well as some illustrative panel simulation examples. There are still some limitations regarding to the model release, e.g., the difficulties to fit both dark and light IV perfectly. Future work involves improving the physics of the compact model and enhancing the functionalities of the panel simulation builder. Please contact sunxingshu@gmail.com regarding any questions/comments about the TAG solar cell model.
References


