1. Introduction

PV Analyzer is a tool for rapid data analysis and parameter extraction from solar cell measurements. Current version analyzes the dark current-voltage (IV) characteristics of solar cells to extract the diode and shunt current parameters. Large area solar cells have a significant parasitic conduction due to parallel shunt paths. In thin film cells in particular these shunt currents are non-ohmic and symmetric with voltage. This tool utilizes the symmetry of shunt current to separate the shunt and diode current components and then uses separate equations to fit the two current components. This separation and fitting method yields parameter values which are free from fluctuations due to parasitic and can be related to physical processes in the device. The tool can also analyze multiple IV data at once, and all the data as well as fit parameters can be downloaded as text files for further analysis.

2. Background

Typical solar cell dark IV is shown in Fig. 1a. The current in low and reverse biases is dominated by parallel shunt current, which has typically represented in the equivalent circuit picture by a parallel resistance as shown in Fig. 1b. However, the shunt current is actually has non-linear dependence on voltage and a space-charge-limited mechanism has been proposed to explain the shunt behavior.

![Fig. 1: (a) Typical dark IV of a solar cell (symbols) showing the diode (solid line) and shunt (dotted line) current components. (b) Conventional equivalent circuit representation of solar cells.](image-url)
The SCL model for non-ohmic parasitic shunts yields the following expression for the shunt current,

\[ I_{SH} = \frac{A_{SH} \varepsilon \mu_c(V)}{L^{2\gamma+1}} V^{\gamma+1}. \]

This symmetric power law expression has been shown to be applicable for many thin film cells. Using this, we can use a parameterized expression for shunt current as follows,

\[ I_{SH} = G_{0,SH} V + I_{0,SH} V^{n_{SH}}; \]

Where \( I_{0,SH} \) is the SCL shunt current magnitude and \( n_{SH} \) is the shunt current power exponent, and \( G_{0,SH} \) is the constant conductance component at low biases. This conductance component is to account for linear conduction of shunt at low bias values (~0.1-0.2 V). Similarly, a parameterized Shockley equation for diode can used to fit the diode current, including the series resistance as,

\[ I_D = I_0 \exp \left( \frac{V - I_D R_S}{n (k_B T / q)} \right). \]

Here \( I_0 \) is the diode saturation current, \( n \) is the diode ideality factor and \( R_S \) is the series resistance. Thus, we have 3 fit parameters for the diode current component, namely, \( I_0, n, \) and \( R_S \), and 3 for the shunt current, i.e., \( I_{0,SH}, n_{SH}, G_{0,SH} \). These, parameters are sufficient to fully characterize the dark current of a thin film solar cell.

Fig. 2: For the same device in Fig. 1a (b). The \(|I|\) vs. \(|V|\) plot (b) showing the symmetry and the ‘clean’ diode current extracted after subtraction (stars).

Another quantity of interest is ideality factor vs. voltage plot. Assuming ideal Shockley equation to hold it is trivial to show that the ideality factor \( n \) can be written as:

\[ n(V) = \frac{q I}{k_B T} \left( \frac{\partial I}{\partial V} \right)^{-1}. \]

For the middle region where the diode equation holds this should be close to fitted ideality factor.
3. ‘Cleaning’ the dark IV

The symmetry of SCL shunt current offers an easy method to isolate the shunt and diode current parts. Notice that the reverse current of the cell (Fig. 1a) is dominated by shunt current. Therefore, we can use the reverse current to obtain the shunt current parameters. Also, using symmetry we observe that \( I_{D,\text{fwd}}(V) = I_{\text{fwd}}(V) - |I_{\text{rev}}(-V)| \). Thus, the forward diode current can be obtained simply by subtracting the reverse current from the forward. This is illustrated in Fig. 2b for the same device in Fig. 1. The plot of \(|I|\) vs. \(|V|\) shows the symmetry (symbols), and after subtraction the ‘cleaned’ diode current follows the Shockley equation current (dotted line) over a much larger voltage range (stars).

4. Using the tool

The first tab in the tool is an information page (Fig. 3), depicting the typical dark IV and the cleaning procedure using symmetry. The equivalent circuit in dark and the diode and shunt equations to be fitted are also shown. A short description of these is also given at the bottom.

---

Fig. 3: (a) PVAnalyzer startup tab showing the dark IV analysis method and the equations to be fitted. (b) Second tab is for data upload, which will appear in the middle box.

The next tab is for IV data input in a text format, which can be done using the upload option at the bottom. The temperature of the measurement can also be specified at the top (default is 300K). Following must be kept in mind for the uploaded data –

- The data must be text in tab or space separated column format with Voltage in 1st column and current in 2nd
- For analyzing multiple IV data simultaneously the data should be in formatted as: V1  I1  V2  I2...
- The sign of current and voltage must correspond, i.e., current should be positive for positive voltage and negative for negative voltage
In order to get good values for all parameters the voltage range should span the entire voltage range from reverse bias (shunt dominated) to high forward bias (series resistance dominated).

After uploading the data, which will be displayed in the middle 'Data' box, the simulate button will start the fitting. The output plots and fit parameters can then be viewed in the same window.

5. Generated outputs

The program detects automatically single or multiple IV data sets, and the outputs are generated accordingly. Different plots or outputs can be selected from the dropdown menu at the top, as show in Fig. 4(a). Any plotted data can be downloaded as an image or comma separated data from the right menu.

Fig. 4: (a) Output plots can be selected from the dropdown menus. (b) All plotted data can be downloaded as image or comma separated data.

The first step is the cleaning of forward IV by shunt subtraction, the generated plots shows $|I|$ vs. $|V|$ and the 'cleaned' forward current after subtraction. As seen in Fig. 5(a), this cleaned current follows the diode equation over a larger range. This subtraction however, is limited by the accuracy of the measurement, and hence the low current values (~ nA) are often noisy (Fig. 5(a)). The calculated $n$ also shows more physical values over a larger range, and has noise at low biases (Fig. 5(b)).
Fig. 5: (a) Cleaned forward IV plot generated by the tool. (b) Calculated ideality factors before and after cleaning are also plotted.

The tool also generates plots for the forward and reverse IV data and the fits obtained. For fitting the forward IV, the noisy data at the low bias must be rejected. The tool does this iteratively by neglecting 1 noisy data point at a time until a good fit is obtained. Forward IV data used for fitting and the corresponding fit obtained are plotted and can be downloaded for comparison. The reverse current is plotted and compared with shunt current parameters (Fig. 6). All the fit parameters are available in the output log file, along with the RMS error and confidence interval values for each of 6 parameters.

Fig. 6: Comparison of forward (a) and reverse (b) IV fits, after rejecting the noisy data at low biases.

For multiple data sets, the tool plots all the above plots for each device. These are plotted as a sequence as shown in Fig. 7(a). To view a particular plot for one of the devices you can use the
slider at the bottom, or use the ‘play’ button at the left to display the plot for all devices in succession. In case of multiple devices, the tool also generates scatter plots of all the fit parameters (Fig. 7(b)), which can be useful to assess the spread in device characteristics across a particular coupon or process run. All fit parameters, and corresponding RMSE values, can be downloaded in text, from the output log.

Fig. 7: (a) Screenshot of cleaning process for multiple IV sets, showing device number 1 (highlighted). (b) Scatter plot of ideality factor for a batch of 8 devices analyzed simultaneously.

6. Remarks

This tool is written in order to handle different solar cell dark IVs, with symmetric shunt contamination. It must be remembered that the cells which do not any shunt current (i.e. infinite shunt resistance) will result in wrong result for shunt current fits. It is also very important for sufficient number of data points in shunt dominated region (low forward bias), as well as series resistance dominated regime (high forward bias), in order to get reasonable numbers for all fit parameters. Finally, in order to ensure good fits, they should look visually appropriate, besides low RMSE values.