Experiment 1

PV Panel Characterization and Modeling

ECE 481: Power Electronics

The objectives of this experiment are:

- To define the requirements on the power electronics to be designed throughout the semester
- To characterize and find numerical parameters for the modeling of a PV panel as a power source
- To become familiar with use of lab equipment

I. Background

Photovoltaic (PV) cells are semiconductor *p*-*n* junction devices, much like diodes. In equilibrium, carrier motion due to drift (motion due to electric field) and diffusion (motion due to carrier concentration) are in balance and there is no external current in the diode. This state is shown in Fig. 1.

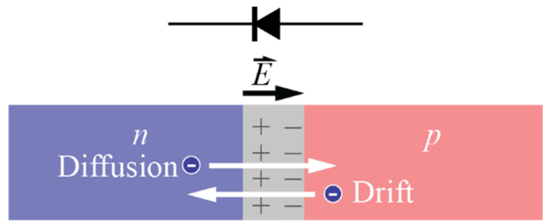


Fig. 1: Cross-section of a *p*-*n* junction in equilibrium

A basic review of semiconductor physics is available online at

http://potenntial.eecs.utk.edu/About.php?topic=PowerSemiconductors

When a *p*-*n* junction is exposed to light, incident photons are absorbed by the material. If the energy of the photon, $E_{photon} = hv$, is greater than the bandgap energy of the material, the absorption of the photon will generate a new electron-hole pair, as shown in Fig. 2.

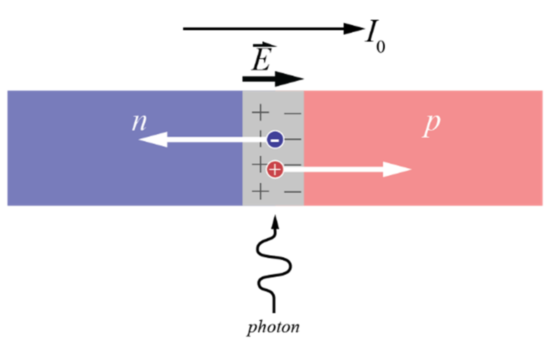


Fig. 2: Electron-hole pair generated by incident photon in a *p*-*n* junction

Any energy in excess of the bandgap energy is converted to heat. The electron-hole pair are quickly swept into their respective majority carrier regions by the electric field. With a steady rate of photons incident on the material (known as insolation, or solar irradiance), the continuous generation and motion of new carriers due to incident light will result in a net current I_0 due to photon absorption. The photocurrent I_0 is proportional to the solar irradiance.

Note that I_0 is in the opposite direction of the normal diode forward-bias current. Thus, if no external circuit is connected, the current from photon absorption I_0 will tend to forward bias the diode and will circulate internally. That is, the increased generation of majority carriers will cause a corresponding increase in diffusion. To use the *p-n* junction as a solar cell, we wish to instead capture this photocurrent by pulling it out of the diode with an external circuit.

PV cell electrical modeling

A simple PV cell model is given in Fig. 3

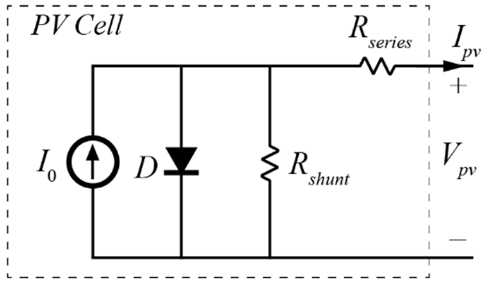


Fig. 3: Circuit model of PV cell

where I_0 is the photocurrent, *D* models the PV cell *p-n* junction and R_{shunt} and R_{series} model defects and material resistivity, respectively. The diode *D* is modeled with the classical *i-v* relationship

$$I_d = I_s\left(e^{\frac{V_D}{nV_T}} - 1\right) \tag{1}$$

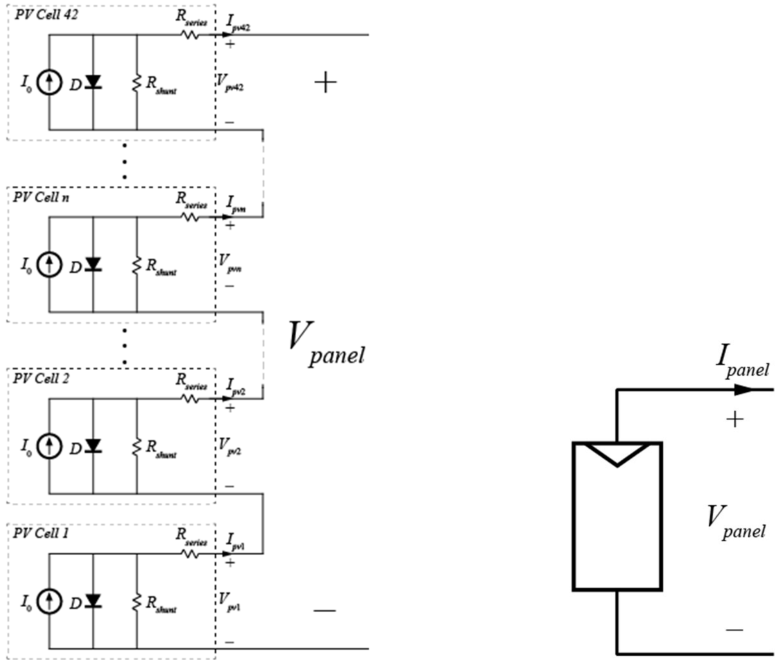
The solar panel used in this course is the Shell ST10,

http://www.solarelectricsupply.com/shell-st10-605

Table I: Shell ST-10 Characteristics

Characteristic	Shell ST10
Cell Strings	1
Number of Cells	42
Cell Type	CIS thin-film
Peak Power	10 W
Peak Voltage	25 V
Peak Current	0.77 A

This panel consists of 42 cells in series, each of the form of Fig. 1. When combined, the complete panel is shown in Fig. 4.



(a) (b)

Fig. 4: (a) Circuit model of complete 42-cell PV panel and (b) schematic symbol for a PV panel

If all cells in the panel have equal solar irradiance, the photocurrent of each cell, I_0 is equal. On earth, on a clear day, solar irradiance can reach to about 1000 W/m^2. Based on the panel datasheet, this corresponds to a photocurrent I_0 = 0.77 A.

Your goal in this experiment is to develop a circuit model of the Shell ST-10 Panel, using experimental measurements to determine diode characteristics I_s and n, and resistances R_{shunt} and R_{series}.

II. Procedure

a. PV Panel Electrical Modeling

In order to determine the electrical model of the panel, we first need experimental measurements.

To avoid having to move equipment outside, we will test indoors, using a current source to mimic the photocurrent that would be generated under a certain solar irradiance. The circuit we will use for testing is shown in Fig. 5, where I_0^* is a current source meant to emulate the photocurrent. If R_{series} is sufficiently small, the characteristics of the panel with respect to changes in I_0^* will mirror those of I_0. The equipment details given in Table II.

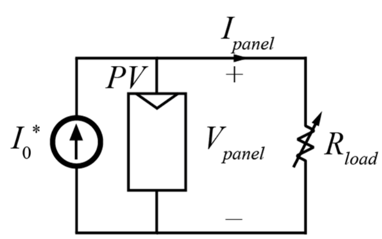


Fig. 5: Test setup to use a benchtop supply to emulate solar irradiance

Table II: Test Circuit Equipment

Component	Equipment	Details
I_0^*	Keithley 2231A	Power Supply Set Supply voltage to 25V and current limit to $0 < I_0^* < 0.77$ A
PV	Shell ST-10	PV Panel
R_{load}	B&K 8500	Electronic Load

Locate the power supply, electronic load, and PV panel. Record the serial number of the panel you tested to ensure that you can re-use the panel that you have modeled in later experiments.

Before connecting anything, set the voltage limit of the power supply to 30 V and the current limit to 0.77 A. This will emulate the photocurrent under maximum outdoor Earth solar irradiance, 1000 W/m^2. Set the electronic load to CR mode, with a resistance of 5 Ω.

Connect the equipment as shown in Fig. 5. The positive (red) terminals of all three device should connect together, and the same with the negative (black) terminals.

Using excel or any other tool for data logging, record the resistance, voltage, and current of the electronic load. Begin increasing the resistance gradually, continuing to record the data. Continue until you reach a resistance where the electronic load voltage is close to 30 V.

> Note: with the electronic load, you may set the load as a constant resistance, voltage, current, or power. Any are fine to use as long as you ensure that you have enough points to characterize the panel, and that the power supply always remains in CC mode. If you are unsure, use CR mode to set a constant resistance.

Be sure to obtain more than 10 points of data, and make sure that you obtain data with sufficient resolution to model the full *i-v* characteristic of the panel. The results should look similar to the 1000 W/m^2 curve from the datasheet, reproduced in Fig. 6. Note that your results may differ somewhat due to variability in manufacturing and aging of the cells.

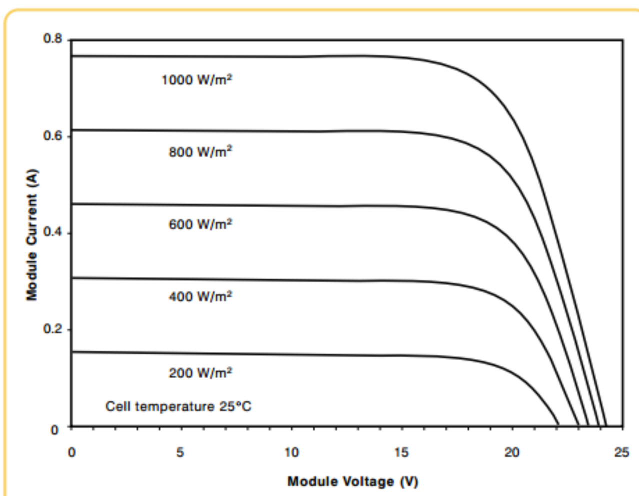


Fig. 6: Shell ST-10 datasheet-reported *i-v* curves.

Repeat the same *i-v* curve measurement for emulated irradiance of 800, 400, and 200 W/m^2. Because I_0 is proportional to solar irradiance, I_0^* should scale linearly with the irradiance level you are emulating. Record the data for each test scenario, and produce a **plot** of the same form as Fig. 6 with all four curves to include in your report.

b. PV Panel Modeling

For the next part of the lab, use LTSpice.

Assume that the panel is well-modeled by circuits in Fig. 3 and Fig. 4. Find values of n, I_s, R_{shunt}, and R_{series} which produce a circuit model that matches your experimental measurements for this panel as closely as you can. You may assume that all 42 cells are identical. There may still be some error in the modeled characteristic relative to the measured one, even with the best parameters.

Plot the measured *i-v* curves of the panel, and your model's *i-v* characteristic on the same axes, for each of the four measured irradiance levels. Also, **plot** the *p-v* characteristic ($P_{panel} = I_{panel} \cdot V_{panel}$ vs V_{panel}) for both the measured data and model output.

In your report, **discuss** the following. Comment on the shape of the curves. At what voltage does maximum power occur? If the panel were directly connected to a 4.2 V lithium ion battery cell, what would happen? Using power electronics between the PV panel and the battery, what type of converter could remedy the situation, and what would its operating point (duty cycle) be at the various solar irradiance levels?

c. Shaded Panel Analysis

If the PV panel is equally shaded, the solar irradiance of each cell reduces, and I_0 reduces proportionally, as tested previously.

Occasionally, only one or a small number of cells will be shaded, while the other cells still have maximum irradiance (e.g. due to a bird landing on the panel). This causes the photocurrent of that cell to reduce to zero, while all other cells continue to have maximum I_0.

Using your model, examine this case. Set one cell's photocurrent to zero, while leaving the remaining cells at full irradiance. **Comment** on what happens to the PV panel as a whole, and what happens to the individual cell that is shaded. Include plots from LTspice to support your discussion. Consider that the PV cell diode D has a reverse breakdown voltage of 5 V.