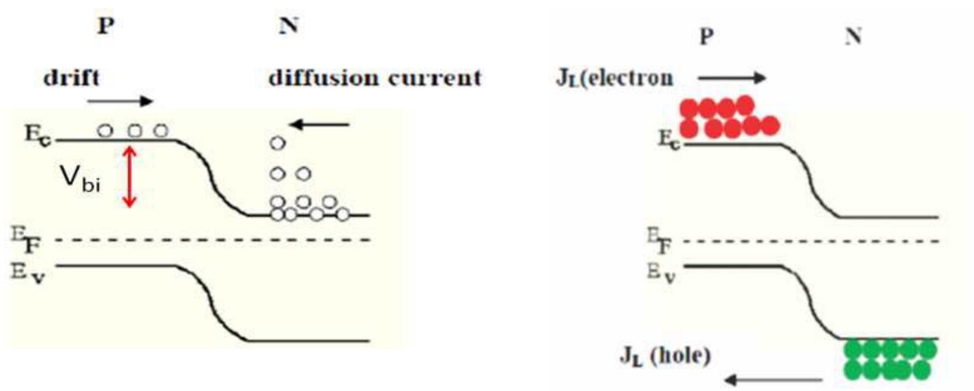
Supporting material for EE236 Experiment on Measuring the current voltage characteristics of a solar cell

How is this experiment different from the previous experiment: A solar cell is just a large area pn junction. The LEDs used in the previous experiments are also pn junctions. The most noticeable difference between these two types of pn junctions is the area of the device. The area of a LED is small compared to the area of a solar cell. A typical industrial solar cell is 15cm x 15 cm pn junction. In contrast a LED is typically 2mmx 2mm pn junction.

Motivation for this experiment: The main motivation of the experiment is to understand how a solar cell works, and figure out the 'quality' of the solar cell you are studying by measuring its fill factor (FF). This can be easily extracted from measuring the I-V characteristics of a solar cell in different light conditions.

Principle of operation: We first examine what happens when light is incident on a semiconductor. Light of energy (hν) greater than the band gap E_g is absorbed. When a photon is absorbed, an electron from the valence band is excited into the conduction band. Each absorbed photon gives rise to a free electron and hole.



The figure on the left shows a pn junction at zero applied bias in the dark. In thermal equilibrium, the diffusion (due to density gradient, independent of electric field) and drift currents (due to applied electric field) cancel out exactly. For simplicity, the hole component is not shown. At zero applied bias, the current is zero.

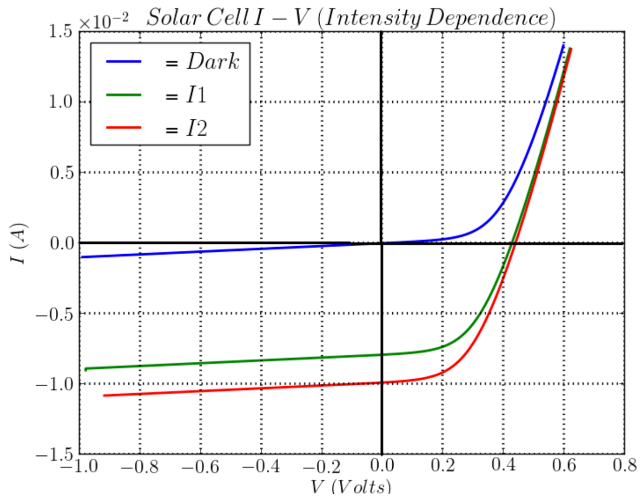
In the dark in forward bias, electrons from the n side are injected into the p side and similarly for holes. In the dark, the diffusion component of the current increases exponentially with voltage (this is what you saw in previous lab).

Under illumination, excess minority carriers are created in the semiconductor. Again, for simplicity the majority carriers are not shown (remember that electrons are minority carriers in p side, and holes are minority carriers in n side). The excess minority carriers are separated by the pn junction and electrons travel to the n side (and holes to the p side), giving rise to current, called as photocurrent. The direction of this photocurrent is opposite to the diffusion current in forward bias.

Thus, the total current (I_{total}) flowing in the diode in forward bias when voltage (V) is applied, can be expressed as:

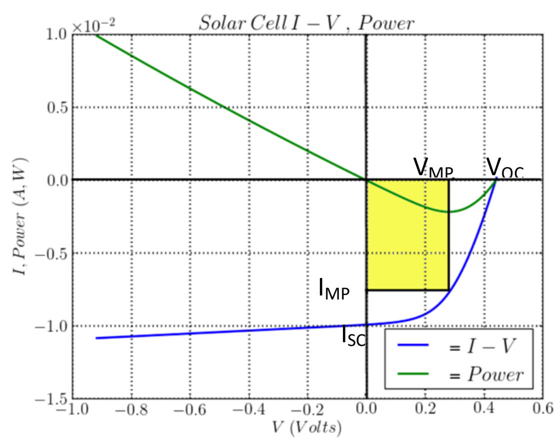
$$I = I_{total} = I_{diffusion} - I_L = I_0 \left[e^{\frac{qV}{\eta kT}} - 1 \right] - I_L$$

where, η is the ideality factor of the diode, I_0 is the saturation current and I_L is the photocurrent. Thus, when the illumination is increased, more photons are absorbed and the magnitude of I_L increases. Due to the difference in sign, this manifests as a down-shift in the I-V curve.



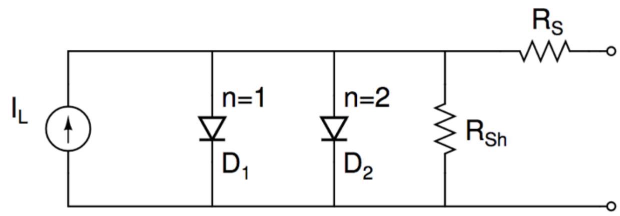
Solar I-V under different illumination levels($I_2 > I_1$)

The figure on the right shows the I-V curve under illumination, along with the power (P = V*I). Given the way we have defined the direction of current flow, positive sign for I indicates that the diode sinks current. Negative sign for I indicates that the diode sources current i.e. it acts as a power supply. This is the regime of operation that we are interested in (we want to generate power with a solar cell). Thus, the 4th quadrant of this I-V or P-V curve is the one we are interested in.



The y-intercept on the I-V curve (i.e. V=0, or short) is called short-circuit current (I_{SC}), and the x-intercept (i.e. I=0, or open) is called open-circuit voltage (V_{OC}). The power at I_{SC} and V_{OC} operation is zero, and maximum power can be obtained by choosing a voltage equal to the value where the yellow rectangle touches the I-V curve. These corresponding values for maximum power are denoted I_{MP} and V_{MP}. The fill factor is defined as ratio of the area under the rectangle (V_{MP}*I_{MP}) to the product (V_{OC}*I_{SC}), thereby telling us how much power the solar cell can really generate as a fraction of the area under the I-V curve in the 4th quadrant.

Modeling the solar cell in terms of familiar components: At low voltages, recombination at the junction dominates and the ideality factor will be close to 2. For higher voltages, ideality factor will be around 1 due to bulk recombination. These are modeled as 2 diodes shown in the circuit diagram below. A real solar cell will also have losses due to parasitic resistive losses in the contacts and the material. This is modeled as a series resistor R_s. The shunt resistor R_{sh} models the manufacturing defects. In most practical cases, this will be a large resistor appearing in parallel with the other components and hence can be neglected. However, the series resistor can reduce output power due to dissipation.



The equation for the current in the solar cell is thus modified to (try deriving this yourself using Kirchoff's current law): (note that V is the voltage across the port on the right hand side, and current I flows across resistor R_s from left to right i.e. the circuit supplies current)

$$I = I_{D1} + I_{D2} - I_{sh} - I_L = I_{0,1}\left[e^{\frac{qV}{kT}} - 1\right] + I_{0,2}\left[e^{\frac{qV}{2kT}} - 1\right] - \frac{V + IR_s}{R_{sh}} - I_L$$

Additional reading: For those that are interested in more details, here are some useful resources:

http://pveducation.org

Good resource for solar cell physics, manufacturing, characterization etc. This site has a lot of information for those interested in learning about the engineering behind making useful solar cell products. (Use the links on the left side of this page for navigation)

http://www.ni.com/white-paper/7230/en/

White paper from National Instruments on additional practical considerations to be aware of when you characterize (i.e. measure) a solar cell.

Challenge question: How much power can you generate using the solar cell that you will measure in this lab experiment? To operate your smartphone on solar power, how many such solar cells (connected in series) would you need? (Hint: your cell phone battery supplies 3.7V, and can typically store 1200mA-Hr. Assuming your phone battery charge lasts for 1 day, it draws on average 1200/24 = 50mA during operation.)