Lecture # 11

Intro to Solar Photovoltaics (PV)

Solar PV Cells

The traditional way to build a solar PV cell is as follows:

Start with Silicon (Si), which has a valence of four (4). Dope the silicon with an element of valence three (3) -- typically Boron (B) is used. The effect of the boron is to produce "wandering" positive charges, also known as "holes", in the material. The material is a "semiconductor".

The boron-doped silicon is called "p-type" material. The "p" stands for wandering positive charges.

of course, overall the material is electrically neutral. The number of positive charges equals the number of negative charges. It is just that more of the positive charges wander about, whereas the negative charges tend to stay "close to home".

Next we slice the block (usually about a 5 inch diameter cylinder) into thin wafers.

The top of the wafer is doped with a valence 5 element -- usually phosphorus (P). This provides wandering electrons, i.e. wandering negative charges.

The phosphorus-doped silicon is called "n-type" material. The "n" stands for wandering negative charges.

To complete our PV cell, we attach a metal sheet at the back, to the P-type material, and we attach thin electrical contacts at the top, to the n-type material.

The top electrical contacts are thin, since we want as much sunlight to get in as possible.

Another thing we do to encourage the letting-in of sunlight is to coat the top with an anti-reflecting coating.

Dark situation

Suppose there is no sunlight incident on the PV cell.

Is anything happening in the cell?

We look at the junction between the p- and n-type materials.

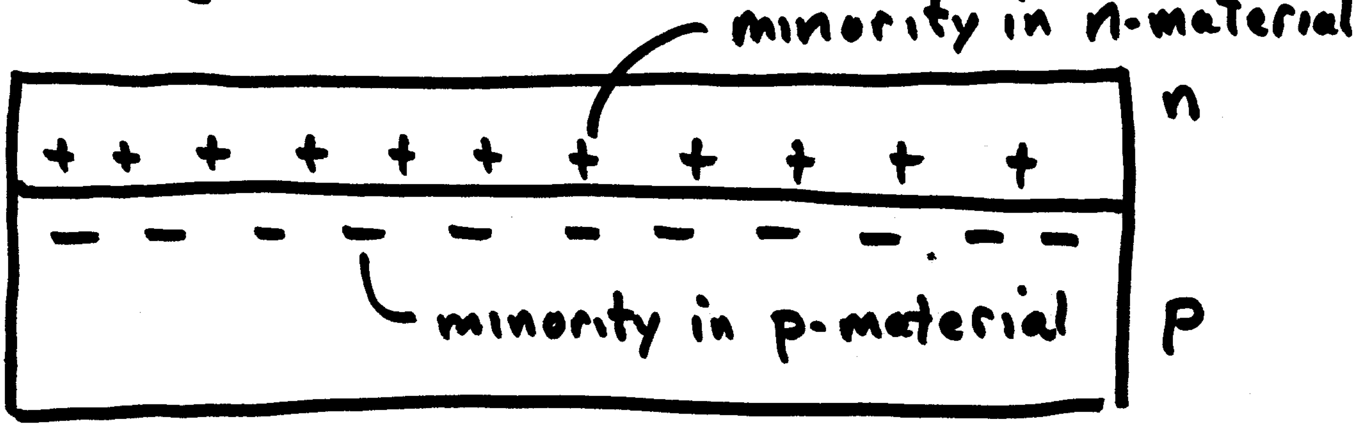
Electrons are wandering in the n-material, and holes are wandering in the p-material.

The electrons will also try to wander over to the p-material, and the holes will try to wander over to the n-material.

A fancier word for wander is diffuse.

The p-material (which has wandering positive charges) actually becomes negatively charged!
And the n-material (which has wandering negative charges) actually becomes positively charged!

An electric field or voltage is built up across the P-n junction



Across the junction, two equal and opposite currents are flowing:

- There is the "generation" current of the minority charges going back to their origin.

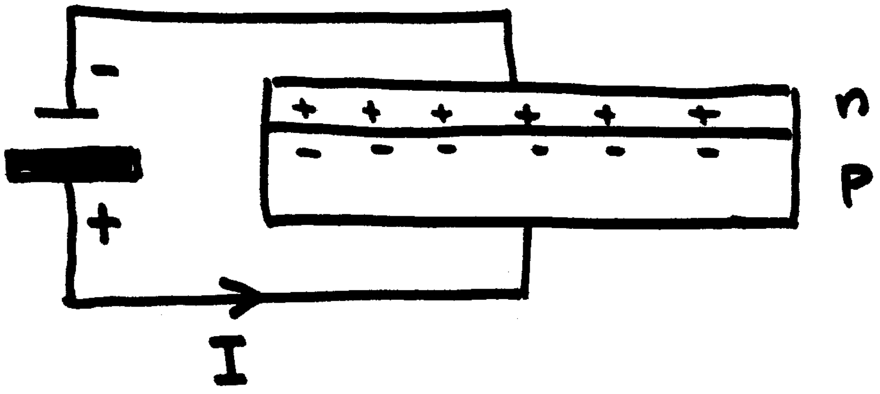
  $$\downarrow^{+} I_g$$

- And there is the "recombination" current of the majority charges diffusing to the "other side".

  $$\uparrow_{+} I_r$$

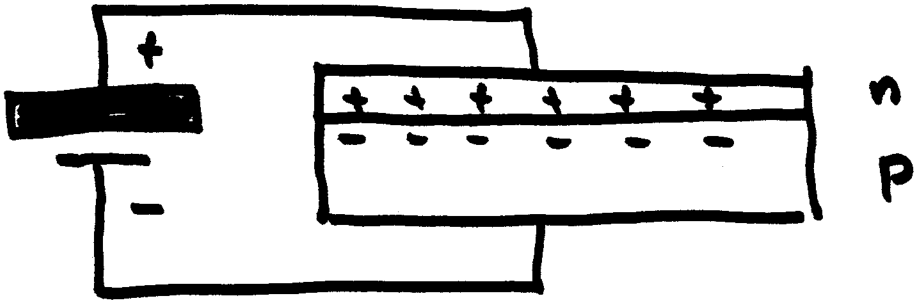
At equilibrium, in the dark, there is <u>no</u> net current.

Now, in the dark, let's impose an external voltage across the PV cell.



The upward current has been increase. Now $I_r > I_g$ and a net current flows across the p-n junction from p to n.
We say the junction is "forward" biased.

Suppose we switch the biasing, as shown below



Now we have made it very difficult for "recombination" current to flow across the junction, since the charges have to "fight" the imposed voltage.

Remember, for "recombination" current, the ⊕ charges move up in our picture and the ⊖ charges move down.

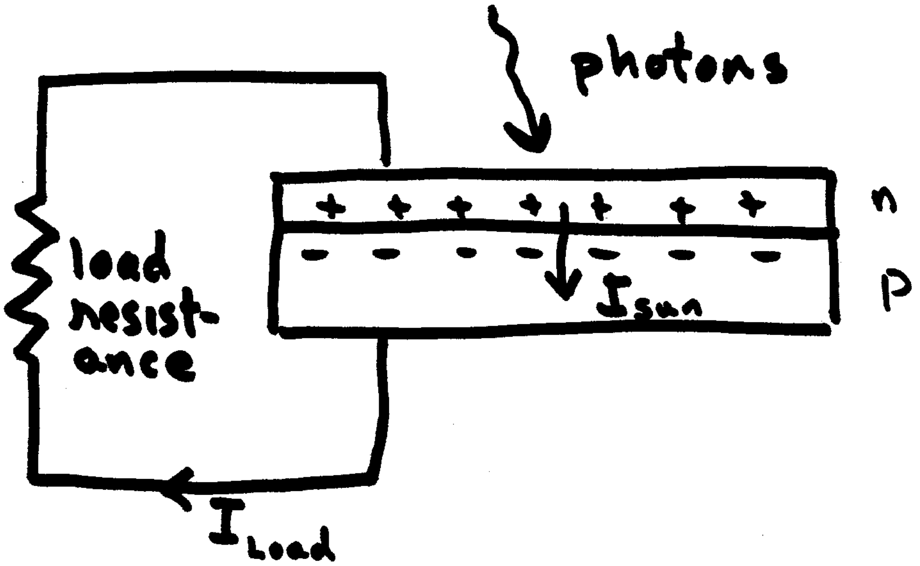
Now $I_r \cong 0$

and there is a (small) generation current, called the dark current, or the saturation current, flowing downward.

$I \cong I_g$

Sunny situation

Now, we let sunlight fall on the PV cell



Photons pass through the thin n-layer and strike atoms in the junction. Someofthe photons have enough energy to make an electron-hole pair when they strike an atom. Precisely, a wandering electron and a wandering hole are created. The hole, being positive, is pulled over to the P-material by the electric field at the junction.

The wandering electron created is pulled over to the n-material by the electric field.

The sunlight has created an electric current!

Note a "side-effect". The sunlight, in causing more wandering holes to enter the P-material and more wandering electrons to enter the n-material, has increased the "recombination" current.

The current through the load, i.e. the external current, is the following:

$$I_{load} = I_{sun} + I_g - I_r$$

With a little rearranging we arrive at the equation linking the current and voltage for the PV cell.

$$I_{load} = I_{sun} - \underbrace{\underbrace{(I_r - I_g)}_{I_{diode}}}_{\text{the PV cell (without sun) is a diode}}$$

Diode theory teaches:

$$I_{diode} = I_r - I_g = I_0\left(e^{qV/KT} - 1\right)$$

when the diode has large forward bias, i.e. $V \gg 0$

$$I_{diode} = I_0 e^{qV/KT}$$

when the diode has large reverse bias

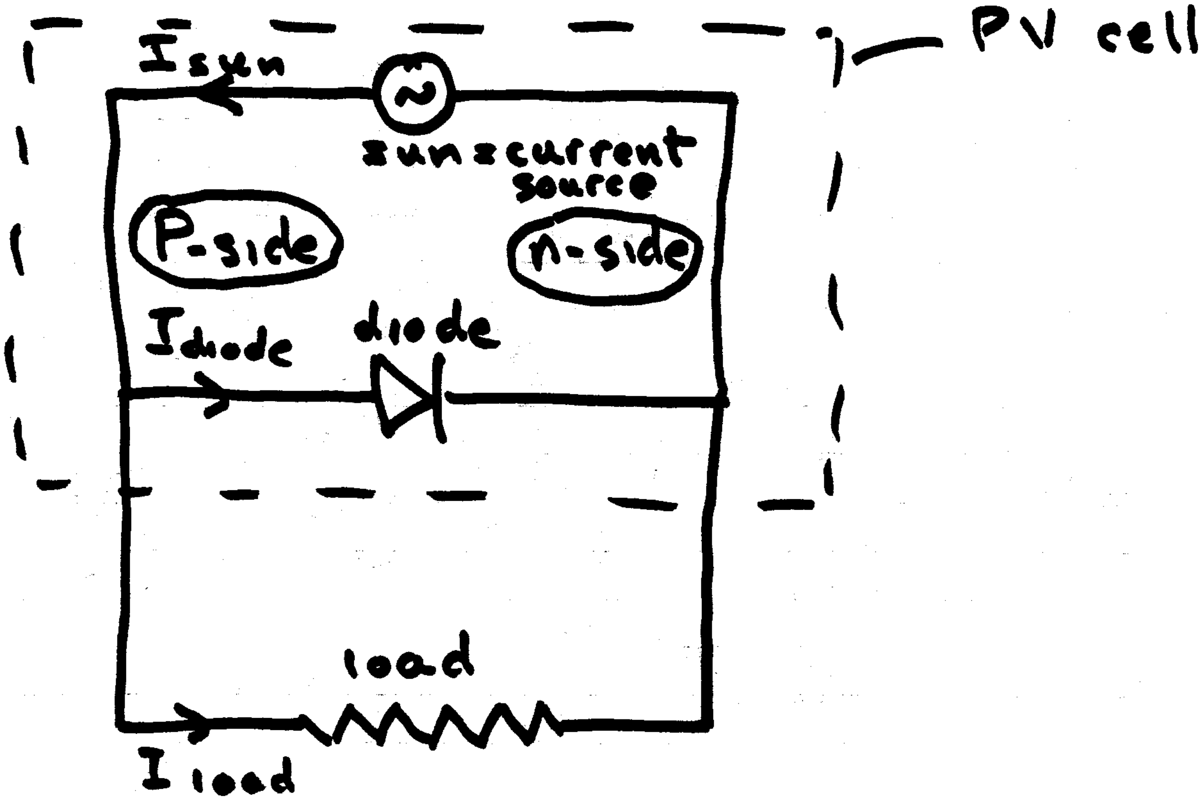
$$I_{diode} = -I_0 = -\text{saturation current}$$

Thus, our equation is

$$I_{load} = I_{sun} - I_o\left(e^{qV/KT} - 1\right)$$

where q = charge = 1.6×10^{-19} joules/volt
V = volts
K = Boltzmann constant
= 1.38×10^{-23} J/K
T = absolute temperature (K)

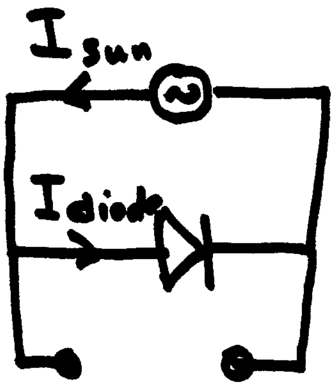
Our circuit diagram is:



Two important limiting cases:

Open circuit:

load resistance
= infinite



$$I_{\substack{load\\oc}} = \frac{V_{oc}}{R_{\cancelto{\infty}{load}}}$$

$$I_{\substack{load\\oc}} = 0$$

In this case $I_{sun} = I_{diode}$

The diode is strongly forward-biased by the wandering charges created by the sunlight.

V_{oc} is found by solving

$$I_{sun} = I_0 \left(e^{qV/kT} - 1 \right)$$

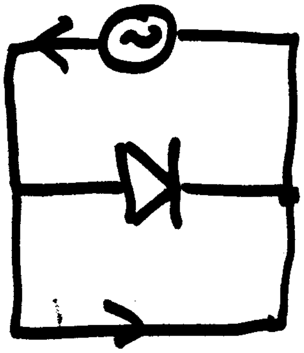
we can solve the equation if we know I_0, the saturation current, and if we know I_{sun}.

Typically, for a PV cell

$$V_{oc} \cong 0.5 - 0.6 \text{ volt}$$

Short circuit:

load resistance = 0



$$V_{sc} = I_{load_{sc}} \cancelto{0}{R_{load}}$$

$$V_{sc} = 0$$

Thus $I_{diode} = 0$

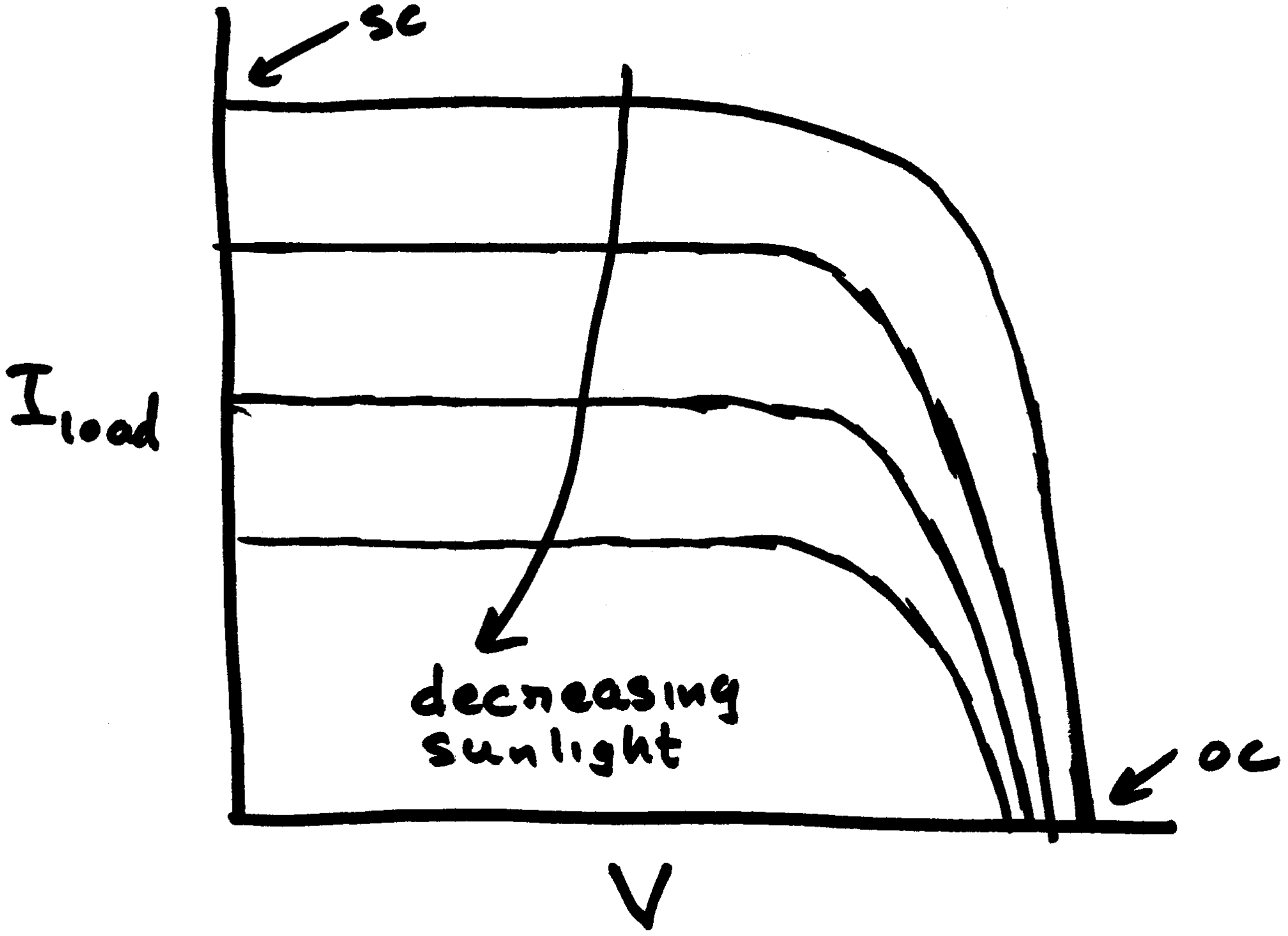
and

$$I_{load_{sc}} = I_{sun}$$

From the short circuit behavior, we know I_{sun}.

In full sunlight (i.e., $G_c = 1000 \; w/m^2$) I_{sun} is about 200 $amps/m^2$.

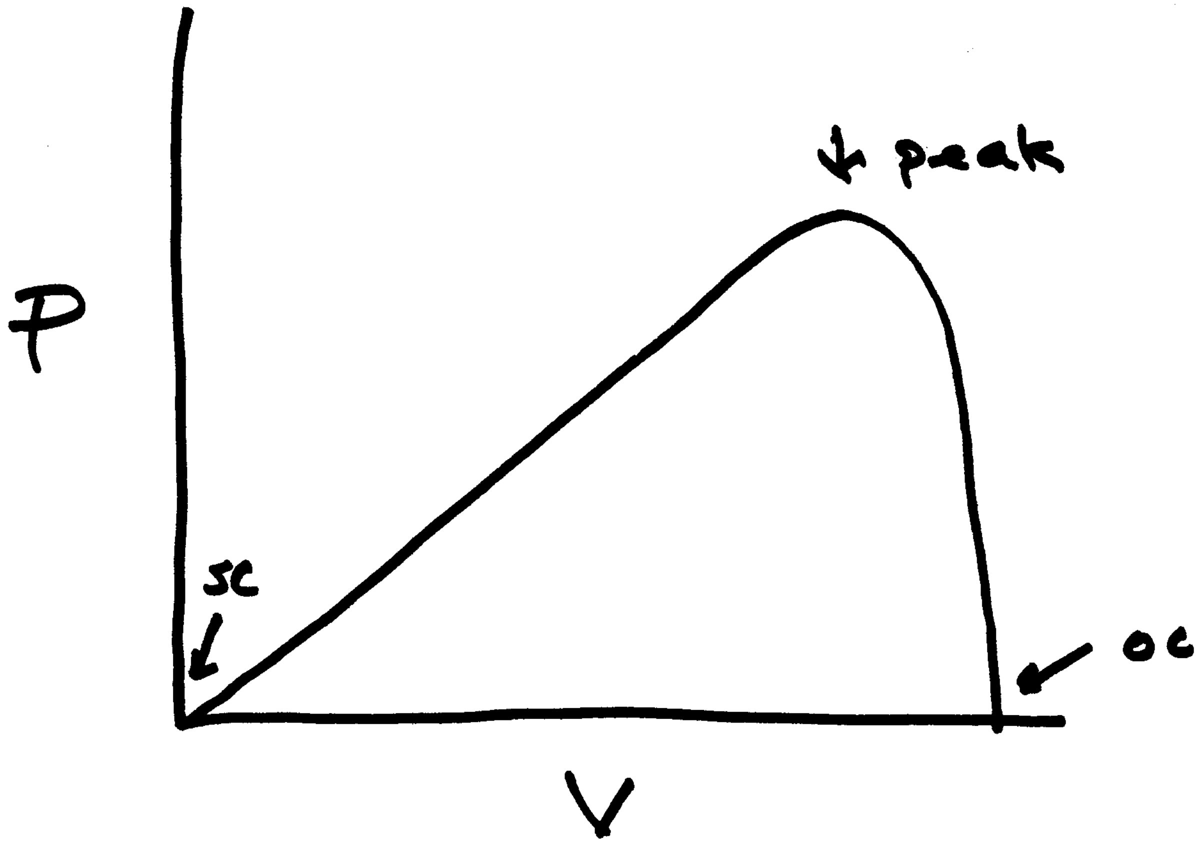
A plot of $I_{load} = I_{sun} - I_0 (e^{qV/kT} - 1)$ looks like the following:



Note: $I_{load_{sc}} = I_{sun}$ depends directly on sunlight (i.e., on G_c) and on the area of the PV cell.

$V_{oc} \cong$ constant

Power (P, watts) = V (volts) × I (amps)
For one value of sunlight, the power curve for a solar PV cell looks like the following:



$P_{peak} \cong 0.75 \times V_{oc} \times I_{sc}$

Note as temperature of PV cell increases, I_0 increases. Therefore V_{oc} decreases. Rule of thumb: 0.4% decrease in power for every 1°C temperature increase.