Lecture 12

Solar Cell in the dark, i.e. N-P junction in the dark

There is no net current in the cell.
There is a balance of two currents

\[ I_n \]

Recombination Current, Net flow of majority carrier, i.e. flow of wandering holes from P to n, seeking an electron, and flow of wandering electrons from n to P, seeking a positive charge.

\[ I_g \]

Generation Current, Net flow of minority carriers from generation of electrons and holes, created from vibrations from heat.
Suppose we apply an external voltage to make the n-side more positive, the p-side more negative.

We have made net upward diffusion of $\oplus$ more difficult -- has to fight increased voltage. \textbf{Reverse bias} \\
$I_n \rightarrow 0$ \\
$I_g$ remains -- small downward current.

Now, switch the external voltage.

We have made net upward diffusion of $\oplus$ easier.

$I_n \gg I_g$ \textbf{Forward bias}
Now let the sun fall on the solar cell (n-p junction). The sunlight creates a downward (n to p) current. This is a negative current on our diagram.

\[
I = I_{\text{diode}} - I_{\text{sun}} = I_0 (e^{\frac{qV}{kT}} - 1) - I_{\text{sun}}
\]

The voltage is like the forward biasing case; since there is a voltage drop across the load, the voltage on P-side > voltage on N-side.
If the load is a very thick wire (very small resistance) connecting the p to n side, the voltage drop across load is essentially zero. 

Then, \( I_{\text{diode}} = I_0 \left( e^{\frac{qV}{kT}} - 1 \right) = I_0 (1-1) \) 

and \( I = I_{\text{load}} = -I_{\text{sun}} = I_{\text{sc}} = 0 \) 

Max current, but since \( V = 0 \), Power = \( IV = 0 \). No electrical work is being done on load.
As the resistance of the load is increased, its voltage drop increases, $V$ increases in our equation and $I_{\text{diode}}$ increases. The net $I$ (I through load) is starting to drop (become more upwards in cell, moving towards $I=0$). However, we don't notice this effect much until the external resistance becomes very large, i.e., as we approach "open circuit".

At open circuit, $I_{\text{load}} = 0$ and

$$I = 0 = I_0(e^{\frac{qV}{kT}} - 1) - I_{\text{sun}}$$

Thus

$$I_0(e^{\frac{qV_{oc}}{kT}} - 1) = I_{\text{sun}} = -I_{SC}$$

\[\text{sun} \quad V_{oc}\]

\[\begin{align*}
\text{(a)} & \quad + \quad + \quad + \quad + \quad + \quad + \\
\text{(b)} & \quad - \quad - I_{G} \quad + \quad I_{SS} \quad + \quad - \quad - \\
\end{align*}\]

essentially (since $I_{G}$ is small), we have balance of $I_{\text{sun}}$ with $I_{G}$.
Redo the plot:
Switch $I_{load}$ to positive

$I = I_{load} = I_{sun} - I_{diode} = I_{sun} - I_0 (e^{V_{oc}/kT} - 1)$

Power = $P = IV$

we would like to run the collector at $P_{max}$, but $R$ of our load may not permit

$I_{optimum} = R V_{optimum}$ for max power

$P_{max}$ much closer to $V_{oc}$ than $I_{sc}$
There are "trackers" that permit running at \( P_{\text{max}} \) -- they adjust \( R \) to keep system at \( P_{\text{max}} \) -- electric power tracker.

Called power point tracking instead of sun tracker.

**Cell to Panel:**

Panel is a number of cells wired in series, typically 30 to 40 cells.

\[
V_{\text{panel}} = V_{\text{cell}} \times \text{number of cells}
\]

\[
I_{\text{panel}} = I_{\text{cell}}
\]

Typical size (for largest of panel)

Panel \( \sim 1 \text{ m}^2 \)

Cell \( \sim 250 \text{ cm}^2 \) \( \sim 16 \text{ cm} \times 16 \text{ cm} \) or \( 18 \text{ cm} \) diameter
For panel, want to know

\[ \begin{align*}
    V_{oc} \\
    I_{sc} \\
    V_{maxP} \approx 0.75V_{oc} \\
    I_{maxP} \\
    P_{max}
\end{align*} \]

for rated sunlight and panel \( T = 25^\circ C \)

See page 96 of text for example.

Cell rated @ \( 25^\circ C \)

AM 1.5 radiation of 1000 W/m²

\[ 1.5 = \frac{1}{\cos \theta} \]

\( \theta \approx 48^\circ \)

Note: since \( I_0 \) increases with \( T_j \)

\( I_{diode} \) increases with \( T \)

and \( I_{load} \) drops with \( T \)

For crystalline Si cells,

0.4% drop in power for each degree C above 25°C.

A cold, strongly radiated cell would give the most power.
Factors affecting efficiency:
1. Top surface contact obstruction: loss ≈ 3%
2. Top surface reflection: loss ≈ 1%
3. Photon energy insufficient: loss ≈ 23%
4. Excess photon energy: loss ≈ 33%
5. Voltage factor - voltage produced at junction less than band gap energy: loss ≈ 20%
6. Curve factor loss #1
   i.e. $P \neq V_{oc} \times I_{sc}$
   Fill factor = $\frac{P_{max}}{V_{oc}I_{sc}}$ (0.88 max for silicon)
   loss ≈ 4%
7. Curve factor loss #2
   $I = I_{sun} - \left( I_{o} (e^{8V_{d} / KT} - 1) \right)$
   not quite followed
   loss ≈ 5%

Delivered Power Si
10 to 17%
<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Cost/m²</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-crystal Si</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi &amp; poly crystal Si</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin film Si</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin film alloys</td>
<td>decreasing</td>
<td>decreasing</td>
</tr>
</tbody>
</table>

Thus Cost/watt doesn't change that much, stays around $4.5 → $5.5/Watt peak for small systems. Maybe $3.50/Wp for large systems.

Balance of System and its cost
How much electrical power?

Example:
Specify a 8 panel, 1000 watt system for your home.

This means in rated sunlight of 1000 W/m² normal to the panels, the system would produce 1000 watts (1 kW) of electricity.

Suppose the efficiency of the panels based on full area is 12.5%.

\[1000 \text{ W/m}^2 \times A \times 0.125 = 1000 \text{ W}\]

\[\Rightarrow A = 8 \text{ m}^2\]

\[\Rightarrow A\text{ one panel} = 1 \text{ m}^2\]
Sunlight:
\[
1000 \text{ w/m}^2 \times 8 \text{ m}^2 = 8000 \text{ w}
\]

Electricity: 1000 w

On average, it is daylight only \(\frac{1}{2}\) the time, 12 hrs. But the early and late hours of the day don't offer much solar energy, especially for panels set at one tilt angle, so we are down to about 8 hrs of useful daylight.

Thus
\[
1000 \text{ w} \times \frac{8}{24} = 333 \text{ average watts}
\]

Now, it is cloudy some of the time. For a place like Phoenix, the result is about 200+ watts average power (i.e. 25% capacity factor).
For places like Seattle, the capacity factor is about 12% \( \Rightarrow \) 120 watts average.

The panels probably cost at least $4000 -- maybe as much as $6000, and we need balance of system: biggest item is inverter.

Total Cost: $7000 to $12000 for our 1000 watts system.

Simple cost:

\[
\frac{200^+ \times 120 \text{ watts} \times 8760 \text{ hr/yr} \times 20 \text{ yrs}}{\$7000 - \$12000}
\]

\[
12 \text{ \$/kwh} - 57 \text{ \$/kwh}
\]

Prediction: "\(200^+, 30\) Seattle at best case (\$7K) \& worst case (120, 20, \$12K)"