Photo-Voltaics and Solar Cells

In this lecture you will learn:

- Photo-Voltaic Cells
- Carrier Transport, Current, and Efficiency
- Solar Cells
- Practical Photo-Voltaics and Solar Cells

Photo-Voltaic Cells

A device that produces a current when exposed to light ....!!
(e.g. a solar cell)

\[ I_L = \text{Short circuit current due to light} \]

Light power = Energy per sec
\[ = P_{inc} \]

\[ \text{External Quantum Efficiency: } \]

\[ EQE = \frac{I}{h\omega} \]
\[ = \frac{|I_L|q}{P_{inc}/h\omega} \]

External quantum efficiency compares the number of electrons produced in the external circuit per second (under a short circuit connection) to the number of photons incident on the device per second.
**Photo-Voltaic Cells Connected to a Load**

Light power = Energy per sec

\[ P_{\text{inc}} = \text{incident light power} \]

\[ I = \text{Current when a load resistor is present} \]

\[ \text{Power Conversion Efficiency:} \]

\[ EQE = \frac{\text{Power delivered to the load}}{\text{incident light power}} = \frac{IR}{P_{\text{inc}}} \]

How much electrical power can be delivered to a load resistor?

It will not be just \( ILR \)

Because \( I \) will change (i.e. will not equal \( I_L \)) when a load resistor is present

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**PN Diodes as Photo-Voltaic Cells**

Consider the standard pn diode:

\[ I = I_D \left( \frac{qV}{eKT} - 1 \right) \]

The pn diode can be used as a photo cell that generates electrical power when exposed to light ....!!

Such a device is called a photo-voltaic cell (e.g. a solar cell)
PN Junction Photo-Voltaic Cells: Some Intuition

1) Suppose a photon creates one electron-hole pair:

2) Quasi neutrality implies that electron and hole stay together

3) If they recombine – end of story!

4) If they diffuse and reach the metal contact, they recombine – end of story!

5) If they diffuse and reach the junction, they separate (because of the E-field in the junction):

6) They contribute one unit of charge to the external current
Boundary Conditions

Short the device output
Shine light uniformly on the P-side
How much current $I_L$ flows in the external circuit?

$$n'(x_p) = \frac{n_i^2}{N_a} \left( \frac{qV_D}{eKT} - 1 \right) = 0$$
$$p'(x_n) = \frac{n_i^2}{N_d} \left( \frac{qV_D}{eKT} - 1 \right) = 0$$

No excess carrier densities at the edges of the depletion region

Carrier Transport

Electron and hole generation rate on the P-side: $G_L$ (units: per unit volume per sec)

Start from the steady state equation:

$$0 = G - R + \frac{1}{q} \frac{\partial J_n(x)}{\partial x} = G - R + D_n \frac{\partial^2 n(x)}{\partial x^2}$$

$$n(x) = n_{po} + n'(x)$$

Equilibrium electron density  Excess electron density

• Then the generation-recombination term becomes:

$$G - R = G_L - \frac{n'(x)}{\tau_n}$$

• And we get:

$$\frac{\partial^2 n'(x)}{\partial x^2} - \frac{n'(x)}{D_n \tau_n} = \frac{G_L}{D_n}$$

Diffusion equation for the excess electron density
Carrier Transport

We need to solve:

\[
\frac{\partial^2 n'(x)}{\partial x^2} - \frac{n'(x)}{D_n \tau_n} = - \frac{G_L}{D_n} \left( \frac{qV_0}{kT} - 1 \right) = 0
\]

\[
n'(-x_p) = \frac{n_f}{N_a} \left( \frac{qV_0}{kT} - 1 \right) = 0
\]

\[
n'(-W_p - x_p) = 0
\]

Assume the short-base limit (no recombination):

\[
\frac{\partial^2 n'(x)}{\partial x^2} = - \frac{G_L}{D_n} \left( \frac{qV_0}{kT} - 1 \right) = 0
\]

\[
n'(-x_p) = \frac{n_f}{N_a} \left( \frac{qV_0}{kT} - 1 \right) = 0
\]

\[
n'(-W_p - x_p) = 0
\]

Solution is:

\[
n'(x) = - \frac{G_L}{2D_n} (x + W_p + x_p)(x + x_p)
\]

Solution is:

\[
n'(x) = - \frac{G_L}{2D_n} (x + W_p + x_p)(x + x_p)
\]

\[
p'(x) = n'(x) = - \frac{G_L}{2D_n} (x + W_p + x_p)(x + x_p)
\]

Quasi-neutrality
Carrier Transport

\[ n'(x) = p'(x) \]

\[ J_n(x) = qD_n \frac{\partial n'(x)}{\partial x} = -qG_L \left( x + \frac{W_p + 2x_p}{2} \right) \]

Minority carriers flow by diffusion only

\[ J_T = J_n(-x_p) = -qG_L \left( \frac{W_p}{2} \right) \]
External Current

\[ I_L = AJ_T = -\frac{q}{2}G_L AW_p \]

Total number of electron-hole pairs generated in the entire P-side per second

External Quantum Efficiency

\[ EQE = \frac{\text{Output current} \cdot q}{\text{Incident light power} \cdot h\omega} = \frac{|I_L| \cdot q}{P_{inc} \cdot h\omega} \]

Suppose every incident photon generates one electron-hole pair, then:

\[ P_{inc} = G_L A(W_p) \]

Then:

\[ EQE = \frac{|I_L| \cdot q}{G_L A(W_p)} = \frac{1}{2} \]

Why just one-half?

Every incident photon generates one electron-hole pair but only half of the generated electron-hole pairs contribute to the external current!
Photo-Excitation in the Depletion Region

Suppose light is now shown on the junction depletion region

1) A photon creates an electron-hole pair

2) They are separated by the large E-field in the junction

3) They contribute one unit of charge to the external circuit

Electron Current (assuming no recombination inside the depletion region):

\[
\frac{1}{q} \frac{\partial J_n(x)}{\partial x} = G - R - G_L + R_o = G_L
\]

\[
\Rightarrow - \int_{-x_p}^{x_n} \frac{\partial J_n(x)}{\partial x} \, dx = \int_{-x_p}^{x_n} G_L \, dx
\]

\[
J_n(-x_p) - J_n(x_n) = q \int_{-x_p}^{x_n} G_L \, dx = qG_L(x_n + x_p)
\]

Hole Current (assuming no recombination inside the depletion region):

\[
\frac{1}{q} \frac{\partial J_p(x)}{\partial x} = G - R - G_L + R_o = G_L
\]

\[
\Rightarrow J_p(x_n) - J_p(-x_p) = q \int_{-x_p}^{x_n} G_L \, dx = qG_L(x_n + x_p)
\]
Photo-Excitation in the Depletion Region

\[ J_n(-x_p) = 0 \]
\[ J_p(x_n) = 0 \]

Electron and Hole Current:
The electric field inside the depletion region sweeps the electrons towards the n-side and the holes towards the p-side. Consequently, it must be that:

\[ J_n(-x_p) - J_n(x_n) = q \int_{-x_p}^{x_n} G_L \, dx = q G_L(x_n + x_p) \]
\[ J_p(x_n) - J_p(-x_p) = q \int_{x_n}^{-x_p} G_L \, dx = q G_L(x_n + x_p) \]

Total Current:

\[ J_T = J_n(x_n) + J_p(x_n) = J_n(-x_p) + J_p(-x_p) \]
\[ = -q G_L(x_n + x_p) \]

External Quantum Efficiency:

\[ EQE = \frac{|I_L|}{G_L A(x_n + x_p)} = 1 \]
Common Photo-Voltaic Structures

A PN Junction Photodetector

The depletion region is not thick enough

A PIN Junction Photodetector

The depletion region can be very thick!

Solar Cells
The circuit current $I$ has two components:

i) The current due to the biased pn junction given as:

$$I_o \left( e^{\frac{qV_D}{KT}} - 1 \right)$$

ii) The current $I_L$ due to photogeneration

These two components can be added together (why?) to give the total current:

$$I = I_o \left( e^{\frac{qV_D}{KT}} - 1 \right) - |I_L|$$
Electrical Power Output

Power delivered to the load resistor:

\[ P_{\text{out}} = i^2 R = -IV_D \]

\[ = \left[ I_0 \left( \frac{qV_D}{e^{RT}} - 1 \right) \right] (V_D) \]

Power delivered to the load is given by the area of the lightly shaded region.

There is an optimal value of the load resistor that allows maximum power delivery to the load.

Energy Conversion Efficiency

Power delivered to the load resistor:

\[ P_{\text{out}} = -IV_D \]

\[ = \left[ I_0 \left( \frac{qV_D}{e^{RT}} - 1 \right) \right] (V_D) \]

External Power Conversion Efficiency:

\[ E = \frac{P_{\text{out}}}{P_{\text{inc}}} = \frac{-IV_D}{P_{\text{inc}}} \]

Fill Factor = \( FF = \frac{\text{Area of lightly shaded region}}{\text{Area of dark shaded region}} \)

\[ = \frac{-IV_D}{-I_{sc}V_{oc}} \]
Design of Silicon Solar Cells

The PERL Si solar cell (Green et al., 1994) Efficiency ~25%

Energy Conversion Efficiencies of Some Common Solar Cells

Typical Performances of Semiconductor Photocells (Green at al., Prog. Photovolt: Res. Appl., 17, 85 (2009))

<table>
<thead>
<tr>
<th>Material</th>
<th>Voc (V)</th>
<th>Jsc (Amp/cm²)</th>
<th>FF (%)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline Si</td>
<td>0.705</td>
<td>42.7</td>
<td>82.8</td>
<td>25.0</td>
</tr>
<tr>
<td>Crystalline GaAs</td>
<td>1.045</td>
<td>29.7</td>
<td>84.7</td>
<td>26.1</td>
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<tr>
<td>Poly-Si</td>
<td>0.664</td>
<td>38.0</td>
<td>80.9</td>
<td>20.4</td>
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<tr>
<td>a-Si</td>
<td>0.859</td>
<td>17.5</td>
<td>63.0</td>
<td>9.5</td>
</tr>
<tr>
<td>CuInGaSe₂ (CIGS)</td>
<td>0.716</td>
<td>33.7</td>
<td>80.3</td>
<td>19.4</td>
</tr>
<tr>
<td>CdTe</td>
<td>0.845</td>
<td>26.1</td>
<td>75.5</td>
<td>16.7</td>
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Design of Solar Cell Modules

The IV characteristics of pn junctions connected in series must identical (or nearly so)