Photo-Voltaics and Solar Cells

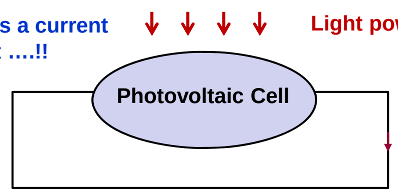
In this lecture you will learn:

- 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)

Light power = Energy per sec $= P_{inc}$

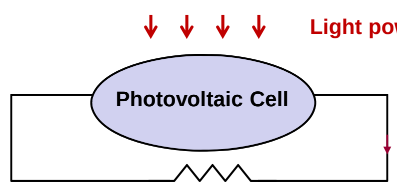


I_L = Short circuit current due to light

External Quantum Efficiency:

$$EQE = \frac{(\text{Output current}) / q}{(\text{Incident light power}) / \hbar\omega} = \frac{|I_L|/q}{P_{inc}/\hbar\omega}$$

Light power = Energy per sec $= P_{inc}$



I = Current when a load resistor is present

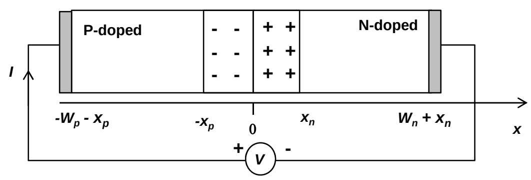
How much electrical power can be delivered to a load resistor?

It will not be just $I_L R$

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

PN Diodes as Photo-Voltaic Cells

Consider the standard pn diode:



$$I = I_o\left(e^{\frac{qV}{KT}} - 1\right)$$

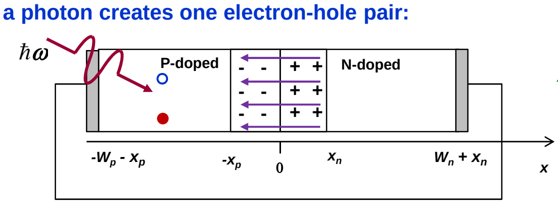
The pn diode can be used as a photo cell that produces a current/voltage when exposed to light ….!!

Such a device is a called a photo-voltaic cell (e.g. a solar cell)

PN Junction Photo-Voltaic Cells: Some Intuition

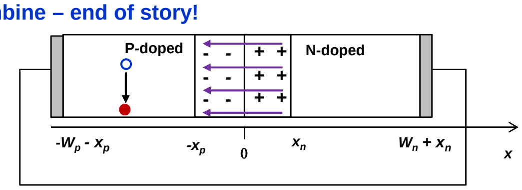
1) Suppose a photon creates one electron-hole pair:

Short circuit operation



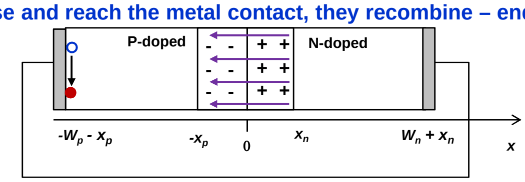
2) Quasi neutrality implies that electron and hole stay together
3) If they recombine – end of story!

$I_L = 0$



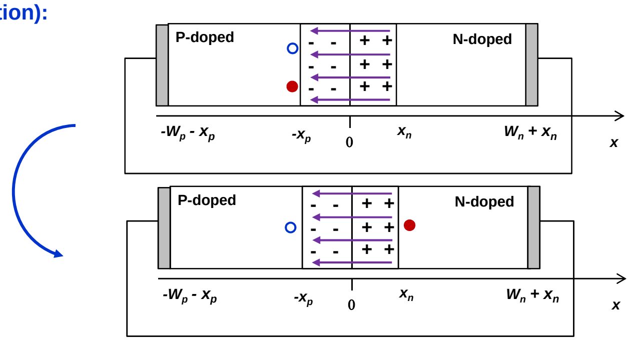
4) If they diffuse and reach the metal contact, they recombine – end of story!

$I_L = 0$

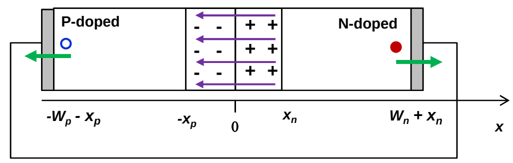


PN Junction Photo-Voltaic Cells: Some Intuition

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



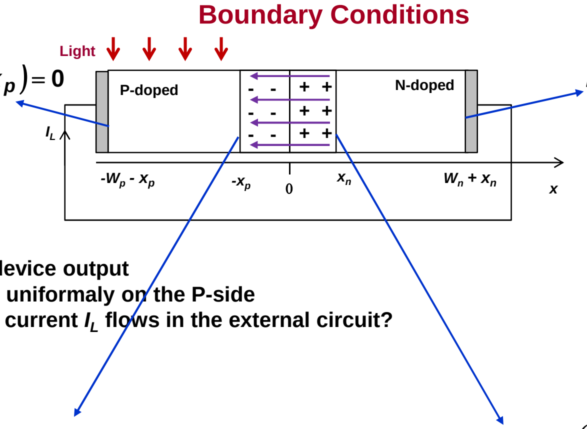
6) They contribute one unit of charge to the external current



Boundary Conditions

$n'(-W_p - x_p) = 0$

$p'(W_n + x_n) = 0$



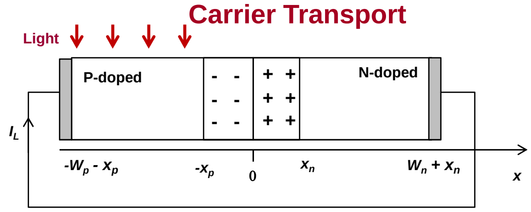
Short the device output
Shine light uniformaly on the P-side
How much current I_L flows in the external circuit?

$$n'(-x_p) = \frac{n_i^2}{N_a}\left(e^{\frac{qV_D}{KT}} - 1\right) = 0$$

$$p'(x_n) = \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right) = 0$$

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

$$n(x) = n_{po} + n'(x) \qquad n_{po} = \frac{n_i^2}{N_a}$$

Equilibrium electron density (n_{po}) — Excess electron density ($n'(x)$)

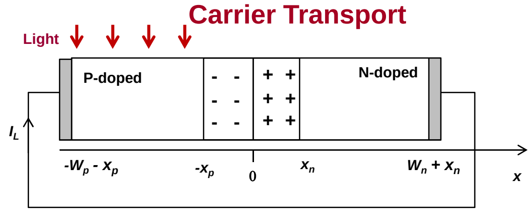
•**Then the generation-recombination term becomes:** $G - R = G_L - \dfrac{n'(x)}{\tau_n}$

•**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:

$$\frac{\partial^2 n'(x)}{\partial x^2} - \frac{n'(x)}{D_n \tau_n} = -\frac{G_L}{D_n} \quad \begin{cases} n'(-x_p) = \dfrac{n_i^2}{N_a}\left(e^{\frac{qV_D}{KT}} - 1\right) = 0 \\ n'(-W_p - x_p) = 0 \end{cases}$$

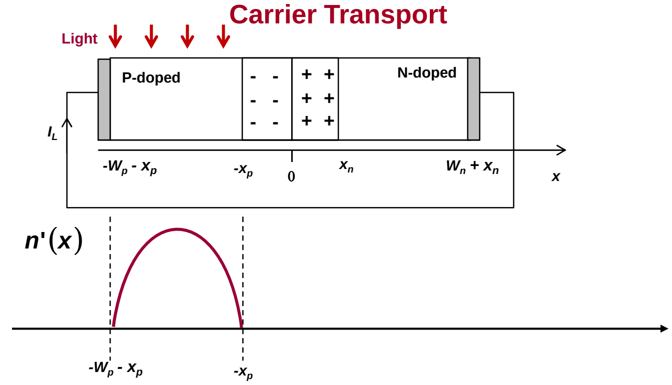
Assume the short-base limit (no recombination):

$$\frac{\partial^2 n'(x)}{\partial x^2} = -\frac{G_L}{D_n} \quad \begin{cases} n'(-x_p) = \dfrac{n_i^2}{N_a}\left(e^{\frac{qV_D}{KT}} - 1\right) = 0 \\ n'(-W_p - x_p) = 0 \end{cases}$$

Solution is:

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

Carrier Transport

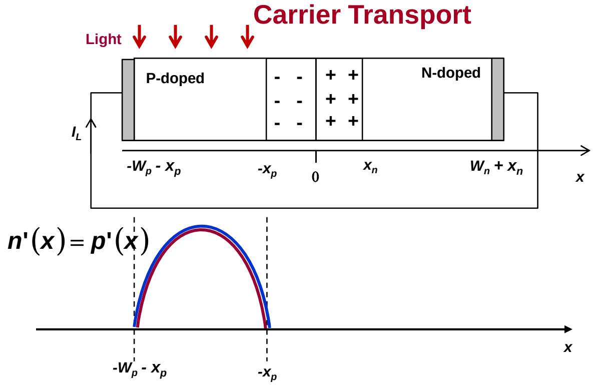


Solution is:

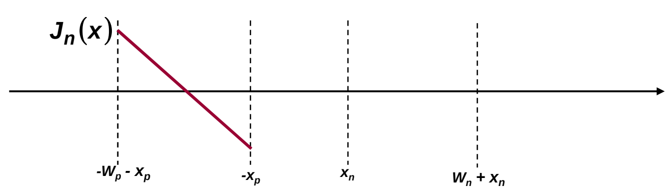
$$n'(x) = -\frac{G_L}{2D_n}\left(x + W_p + x_p\right)\left(x + x_p\right)$$

$$p'(x) = n'(x) = -\frac{G_L}{2D_n}\left(x + W_p + x_p\right)\left(x + x_p\right) \rightarrow \text{Quasi-neutrality}$$

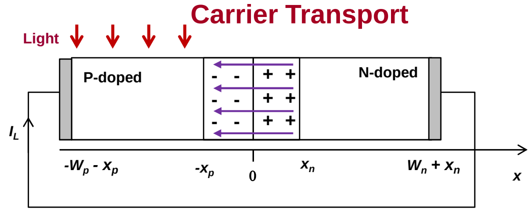
Carrier Transport



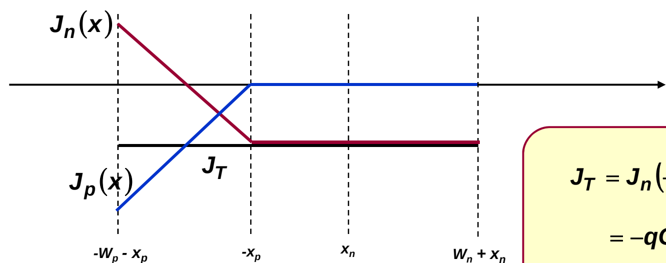
$$J_n(x) = qD_n \frac{\partial n'(x)}{\partial x} = -qG_L\left(x + \frac{W_p + 2x_p}{2}\right) \rightarrow \text{Minority carriers flow by diffusion only}$$



Carrier Transport

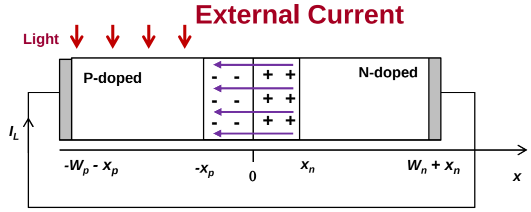


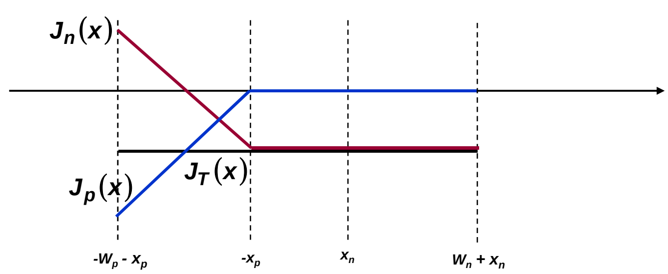
$$J_n(x) = qD_n \frac{\partial n'(x)}{\partial x} = -qG_L\left(x + \frac{W_p + 2x_p}{2}\right)$$



$$J_T = J_n(-x_p) = -qG_L\left(\frac{W_p}{2}\right)$$

External Current

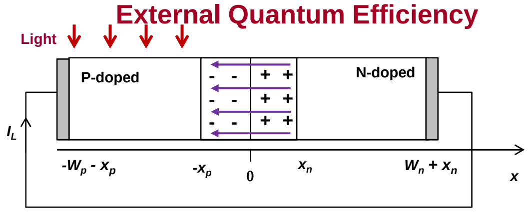




$$I_L = AJ_T(x) = -\frac{q}{2}G_L AW_p$$

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

External Quantum Efficiency



$$EQE = \frac{\text{(Output current) / } q}{\text{(Incident light power) / } \hbar\omega} = \frac{|I_L|/q}{P_{inc}/\hbar\omega}$$

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

$$\frac{P_{inc}}{\hbar\omega} = G_L A(W_p)$$

Then:

$$EQE = \frac{|I_L|/q}{G_L A(W_p)} = \frac{1}{2}$$

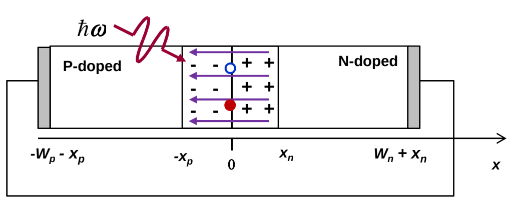
Why just one-half?

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

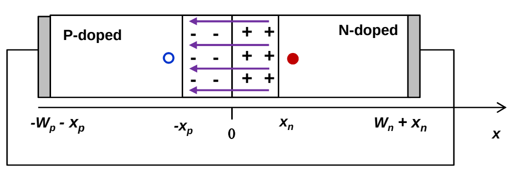
Photo-Excitation in the Depletion Region

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

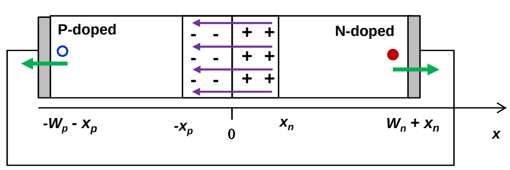
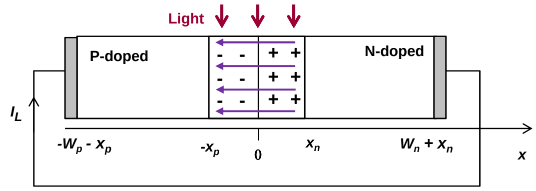


Photo-Excitation in the Depletion Region

Suppose light is now shown on the junction region



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

$$-\frac{1}{q}\frac{\partial J_e(x)}{\partial x} = G - R \approx G_o + G_L - R_o = G_L$$

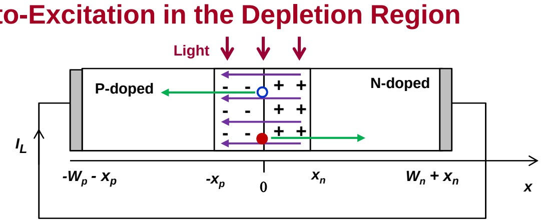
$$\Rightarrow J_e(-x_p) - J_e(x_n) = q\int_{-x_p}^{x_n} G_L \, dx = qG_L(x_n + x_p)$$

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

$$\frac{1}{q}\frac{\partial J_h(x)}{\partial x} = G - R \approx G_o + G_L - R_o = G_L$$

$$\Rightarrow J_h(x_n) - J_h(-x_p) = q\int_{-x_p}^{x_n} G_L \, dx = qG_L(x_n + x_p)$$

Photo-Excitation in the Depletion Region



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:

$$J_e(-x_p) = 0$$

$$J_h(x_n) = 0$$

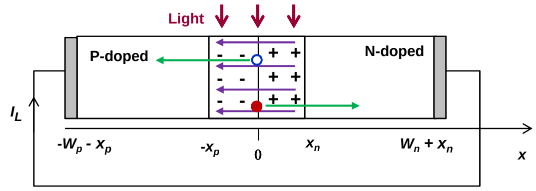
Therefore,

$$J_h(-x_p) = J_e(x_n) = -qG_L(x_n + x_p)$$

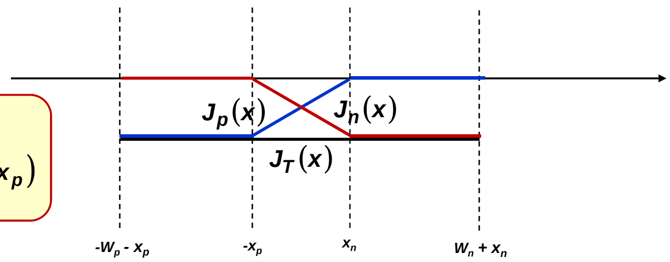
Total Current:

$$J_T = J_e(x_n) + J_h(x_n) = J_e(-x_p) + J_h(-x_p)$$
$$= -qG_L(x_n + x_p)$$

Photo-Excitation in the Depletion Region



$$I_L = AJ_T$$
$$= -qG_L A(x_n + x_p)$$



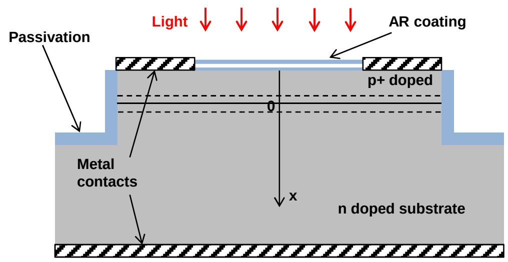
External Quantum Efficiency:

$$EQE = \frac{|I_L|/q}{G_L A(x_n + x_p)} = 1$$

Common Photo-Voltaic Structures

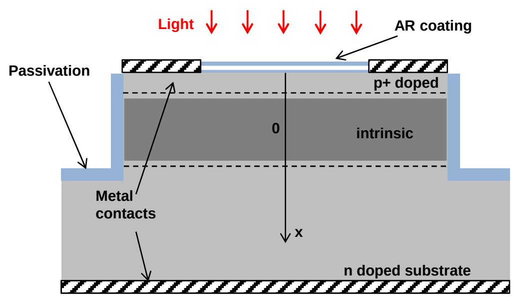
A PN Junction Photodetector

The depletion region is not thick enough

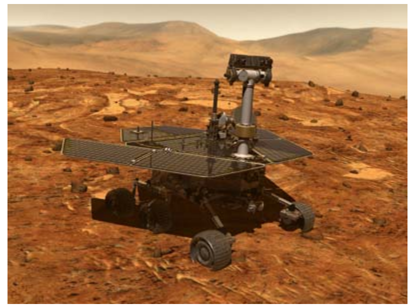


A PIN Junction Photodetector

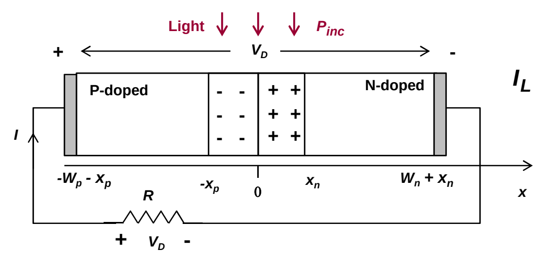
The depletion region can be very thick!



Solar Cells



PN Photo-Voltaic Cells as Solar Cells



$$I_L = -qG_L A(x_n + x_p)$$

The circuit current *I* has two components:

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

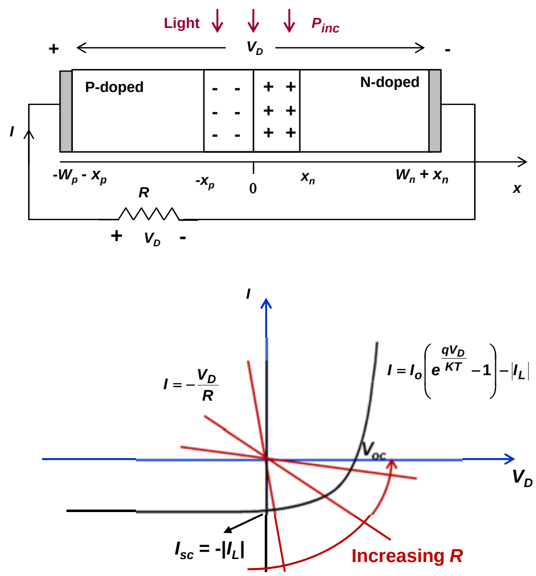
$$I_o\left(e^{qV_D/KT} - 1\right)$$

ii) The current I_L due to photogeneration

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

$$I = I_o\left(e^{qV_D/KT} - 1\right) - |I_L|$$

Electrical Characteristics



We have:

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

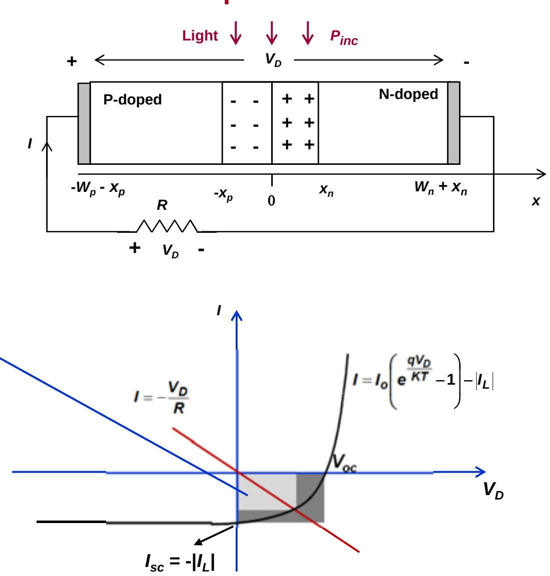
We also have the load-line equation:

$$IR + V_D = 0$$

Solution of these two equations gives the operating point

Graphical solution: →

Electrical Power Output



Power delivered to the load resistor:

$$P_{out} = -IV_D$$
$$= -\left[I_o\left(e^{\frac{qV_D}{KT}} - 1\right) - |I_L|\right](V_D)$$

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

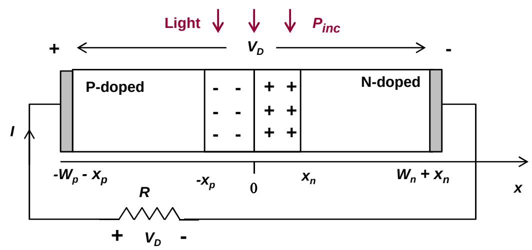
There is an optimal value of the load resistor that allows maximum power delivery to the load

Energy Conversion Efficiency

Power delivered to the load resistor:

$$P_{out} = -IV_D$$

$$= -\left[I_o \left(e^{\frac{qV_D}{KT}} - 1 \right) - |I_L| \right] (V_D)$$

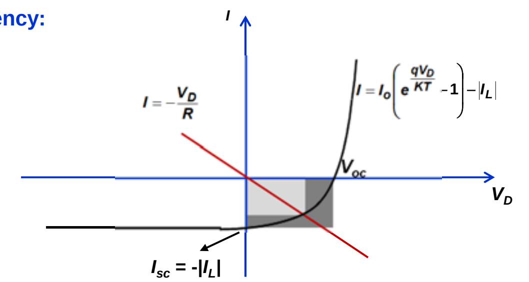


External Power Conversion Efficiency:

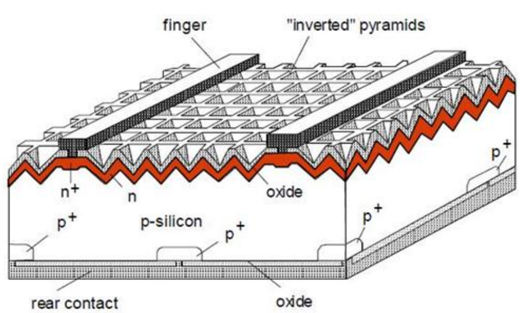
$$E = \frac{P_{out}}{P_{inc}} = \frac{-IV_D}{P_{inc}}$$

Fill Factor = *FF* = $\dfrac{\text{Area of lightly shaded region}}{\text{Area of dark shaded region}}$

$$= \frac{-IV_D}{-I_{sc}V_{oc}}$$



Design of Silicon Solar Cells



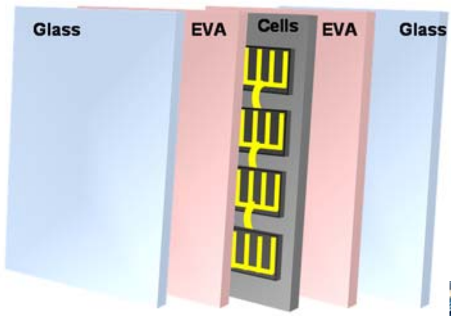
The PERL Si solar cell (Green et al., 1994) Efficiency ~25%

Energy Conversion Efficiencies of Some Common Solar Cells

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

Material	Voc (V)	Jsc (Amp/cm^2)	FF (%)	Efficiency (%)
Crystalline Si	0.705	42.7	82.8	25.0
Crystalline GaAs	1.045	29.7	84.7	26.1
Poly-Si	0.664	38.0	80.9	20.4
a-Si	0.859	17.5	63.0	9.5
CuInGaSe$_2$ (CIGS)	0.716	33.7	80.3	19.4
CdTe	0.845	26.1	75.5	16.7

Design of Solar Cell Modules



A solar cell module

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