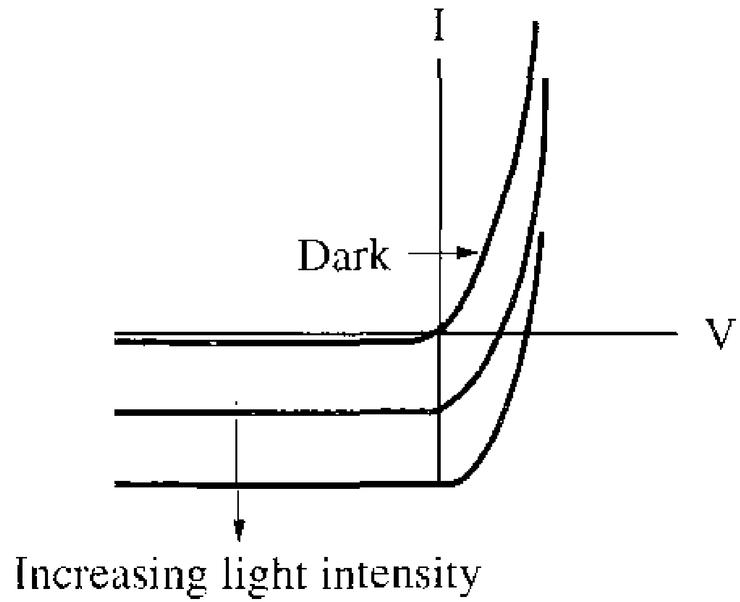
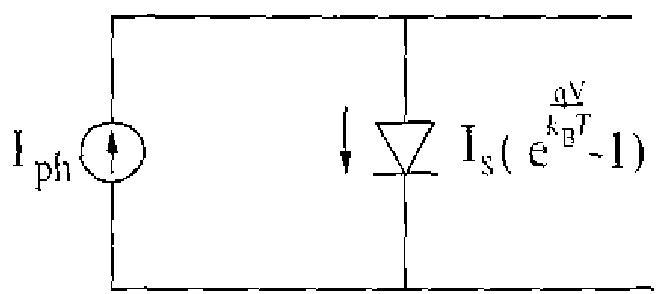
Solar cell I-V curves and equivalent circuit

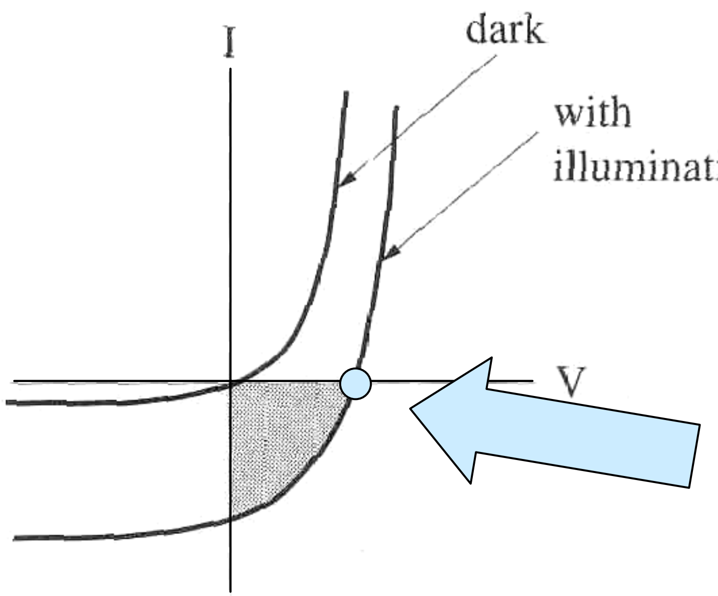
$$I = I_S\left[\mathbf{exp}\left(\frac{qV}{kT}\right) - 1\right] - I_{Ph}$$

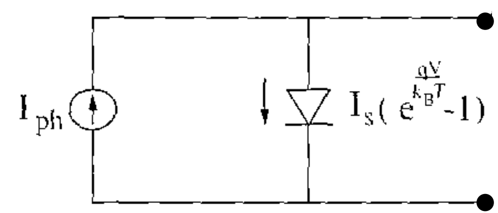


$$I_{ph} = qAG(L_h + L_e)$$



Open-circuit solar cell





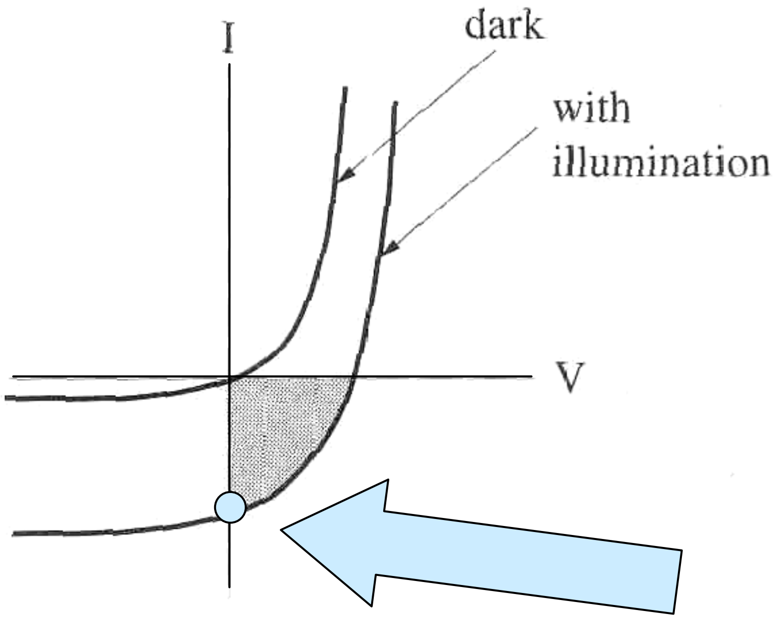
$$I = \left\{ I_S \left[\mathbf{exp}\left(\frac{qV_{oc}}{kT} \right) - 1 \right] - I_{ph} \right\} = 0$$

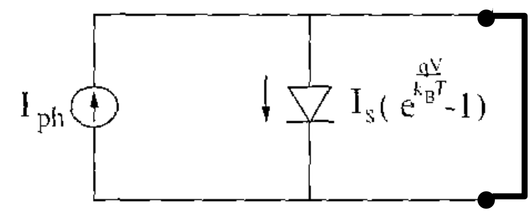
the current is zero; the solar cell delivers maximum voltage;
The output power P = I ×V =0

The open-circuit voltage, at I=0: $V_{oc} = \frac{k_B T}{q} ln \left[\frac{I_{ph}}{I_S} + 1 \right] \cong \frac{k_B T}{q} ln \left[\frac{I_{ph}}{I_S} \right]$

Note, the maximum achievable $\boldsymbol{V_{OCmax} = V_{bi}}$

Short-circuit solar cell



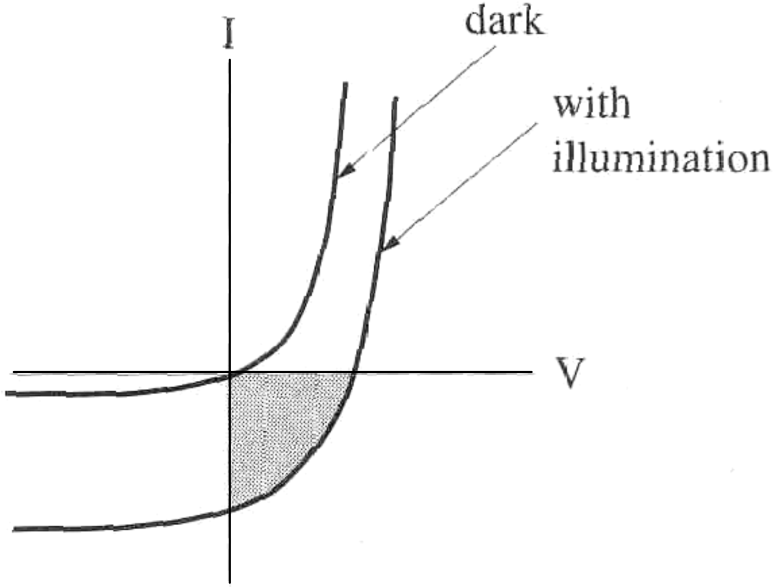


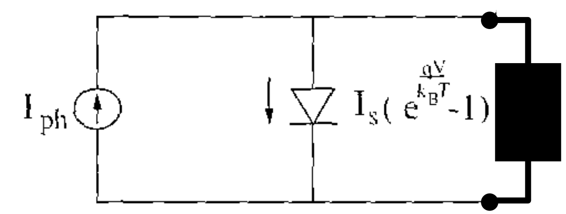
$$I_{sc} = \left\{ I_S \left[\mathbf{exp}\left(\frac{qV}{kT}\right) - 1 \right] - I_{ph} \right\}_{V=0}$$

the voltage across the diode is zero;
the solar cell provides maximum current into the circuit;
The output power P = I ×V =0

The short-circuit current, at V=0: $I_{sc} = I_{ph} = -qAG(L_h + L_e)$

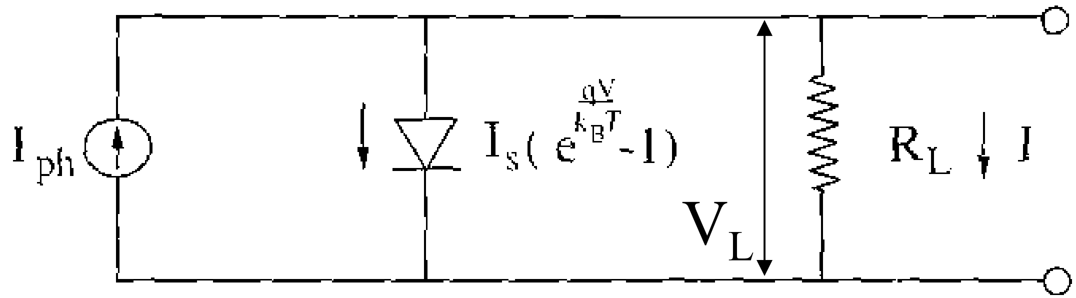
Solar cell with an arbitrary load

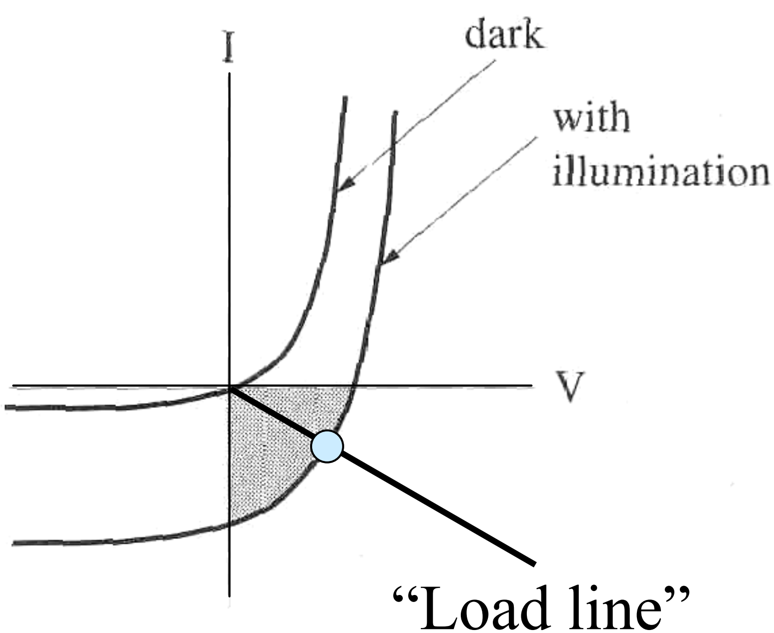




The dashed region shows the range of external bias where the energy is ***generated:*** $P_{dis}=V\times I < 0$

Equivalent circuit of the solar cell with active load.





Diode equation:

$$I = I_S\left[\mathbf{exp}\left(\frac{qV}{kT}\right)-1\right]-I_{Ph}$$

Kirchhoff voltage law:

$$V + V_L = 0; \;\; or \;\; V_L = -V$$

Load equation:

$$I = V_L / R_L = -V / R_L$$

The output power of the solar cell

$$P = IV = I_S V \left(e^{qV/k_BT} - 1\right) - I_{ph} V$$

The condition for maximum power

$$\frac{d}{dV}\left[I_S V \left(e^{qV/k_BT} - 1\right) - I_{ph} V\right] = 0$$

This leads to the equation:

$$I_S \left(e^{qV/k_BT} - 1\right) + I_S \frac{qV}{k_BT} e^{qV/k_BT} = I_{ph}$$

(Here k_B is the Boltzmann constant, same as k)

From this, the optimal voltage can be estimated:

$$I_S\, e^{qV_m/kT} + \frac{qV_m}{kT} I_S\, e^{qV_m/kT} \approx I_{ph};$$

$$I_{ph} \approx I_S\, e^{qV_m/kT}\left(1+\frac{qV_m}{kT}\right)$$

Compare V_m to the open-circuit voltage V_{OC}: $\quad I_{ph} = I_S\, e^{qV_{OC}/kT}$

From this, $\quad V_m = V_{OC} - \frac{kT}{q} ln\left(1+\frac{qV_m}{kT}\right)$

Note that $\frac{kT}{q} ln\left(1+\frac{qV_m}{kT}\right) \approx 0.026\,\mathbf{ln}\left(1+1/0.026\right) = 0.096V$

Also, note that ln(x) is a slow function of x. Hence,

$$ln\left(1+\frac{qV_m}{kT}\right) \approx ln\left(1+\frac{qV_{OC}}{kT}\right)$$

The optimal voltage is then: $\quad V_m \approx V_{OC} - \frac{kT}{q} ln\left(1+\frac{qV_{OC}}{kT}\right)$

The optimal current of the solar cell
(corresponding to the maximum output power)

Given the optimal voltage is V_m,
the corresponding maximum current can be found as

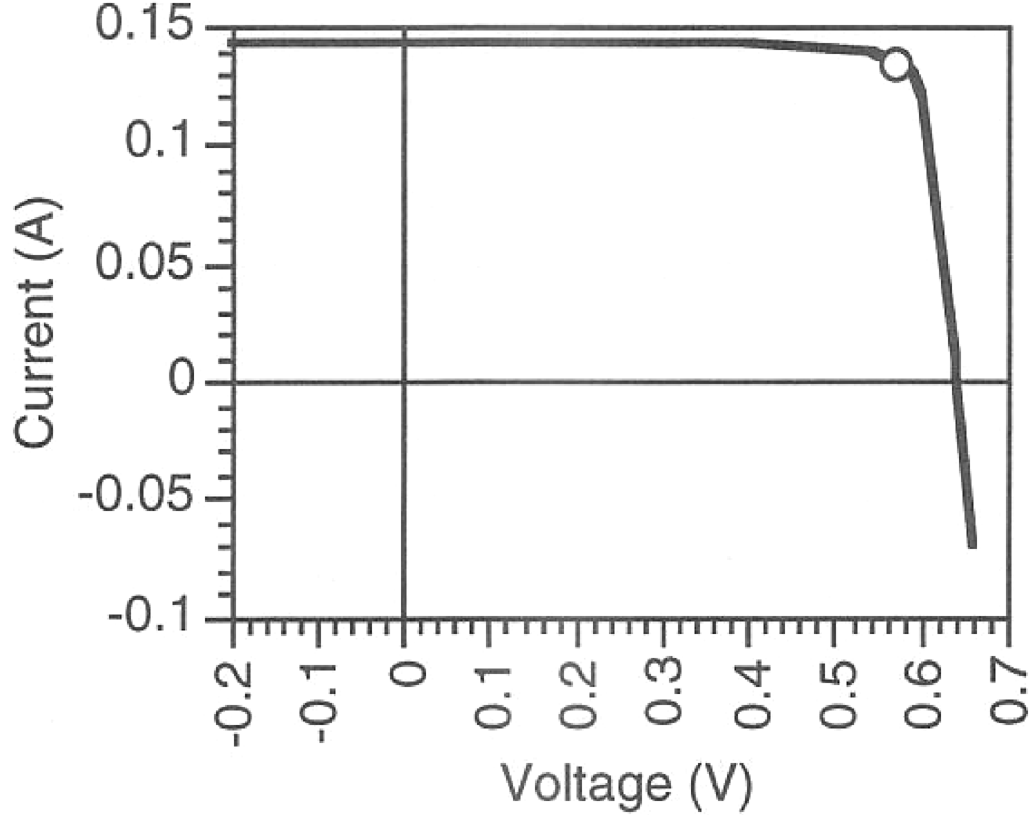
$$I_m = I_S \left[\mathbf{exp}\left(\frac{qV_m}{kT} \right) - 1 \right] - I_{Ph}$$

Where $V_m = V_{OC} - \frac{kT}{q} ln\left(1 + \frac{qV_{OC}}{kT} \right)$ and $V_{OC} \approx \frac{kT}{q} ln\left(\frac{I_{ph}}{I_S} \right)$

after transformations, $$I_m = -I_{ph}\left(1 - \frac{kT}{qV_m} \right)$$

Note that $kT/q \approx 0.026\ V$ and hence, under strong excitation

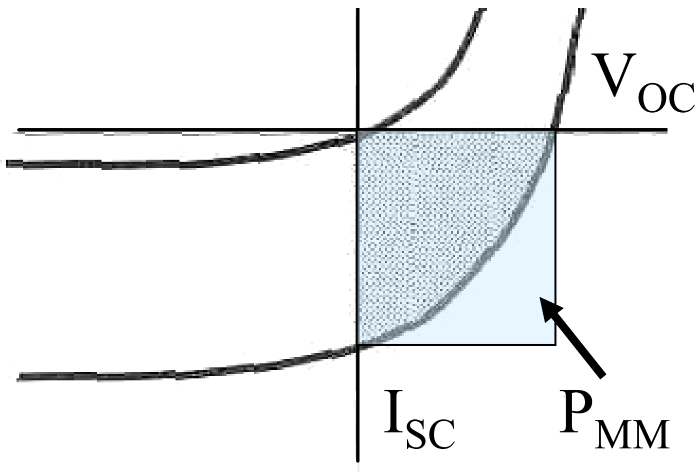
$kT/(qV_m) << 1$ *and* $\mathbf{I_m \approx -I_{ph}}$



Measured current-voltage characteristics of a high efficiency silicon solar cell. Open circle voltage, *Voc* = 0.6411 V, short-circuit current density, *Jsc* = 35.48 mA/cm^2, fill factor 0.822, efficiency 18.70%. Open circle denotes the maximum power point.

(after M. A. Green, A. W. Blakers, J. Shi, E. M. Keller, and S. R. Wenham, IEEE Trans. Electron. Dev., ED-31, No. 5, p. 679, 1984, © IEEE, 1984).

Solar cell fill factor



The maximum voltage that the solar cell can develop is V_{OC};
The maximum current of the solar cell is I_{SC}.
If the solar cell could simultaneously deliver the maximum voltage and the maximum current, the maximum power would be $P_{MM} = V_{OC} \times I_{SC}$
The actual power is given by
$P_m = V_m \times I_m$
The solar cell fill factor is thus defined as

$$FF = \frac{I_m V_m}{I_{SC} V_{OC}}$$

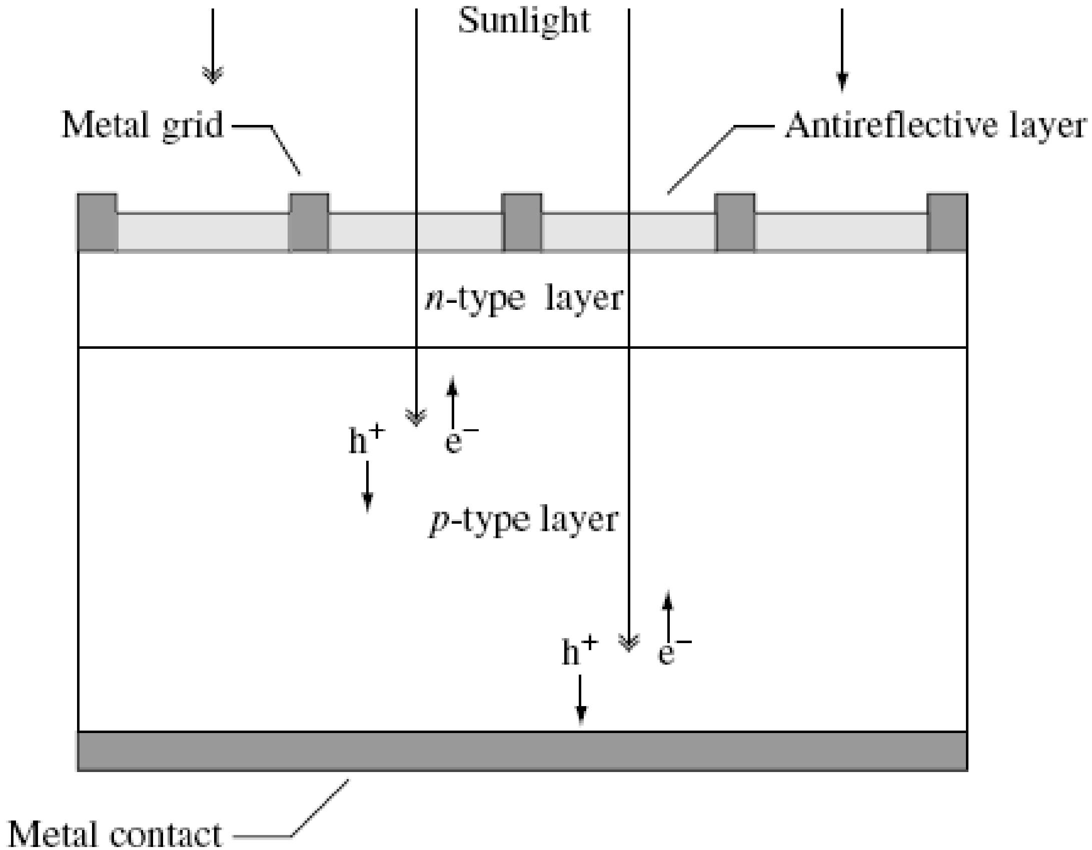
Solar cell conversion efficiency

A solar cell's *energy conversion efficiency* (η, "eta"), is the percentage of power converted from absorbed light to electrical energy

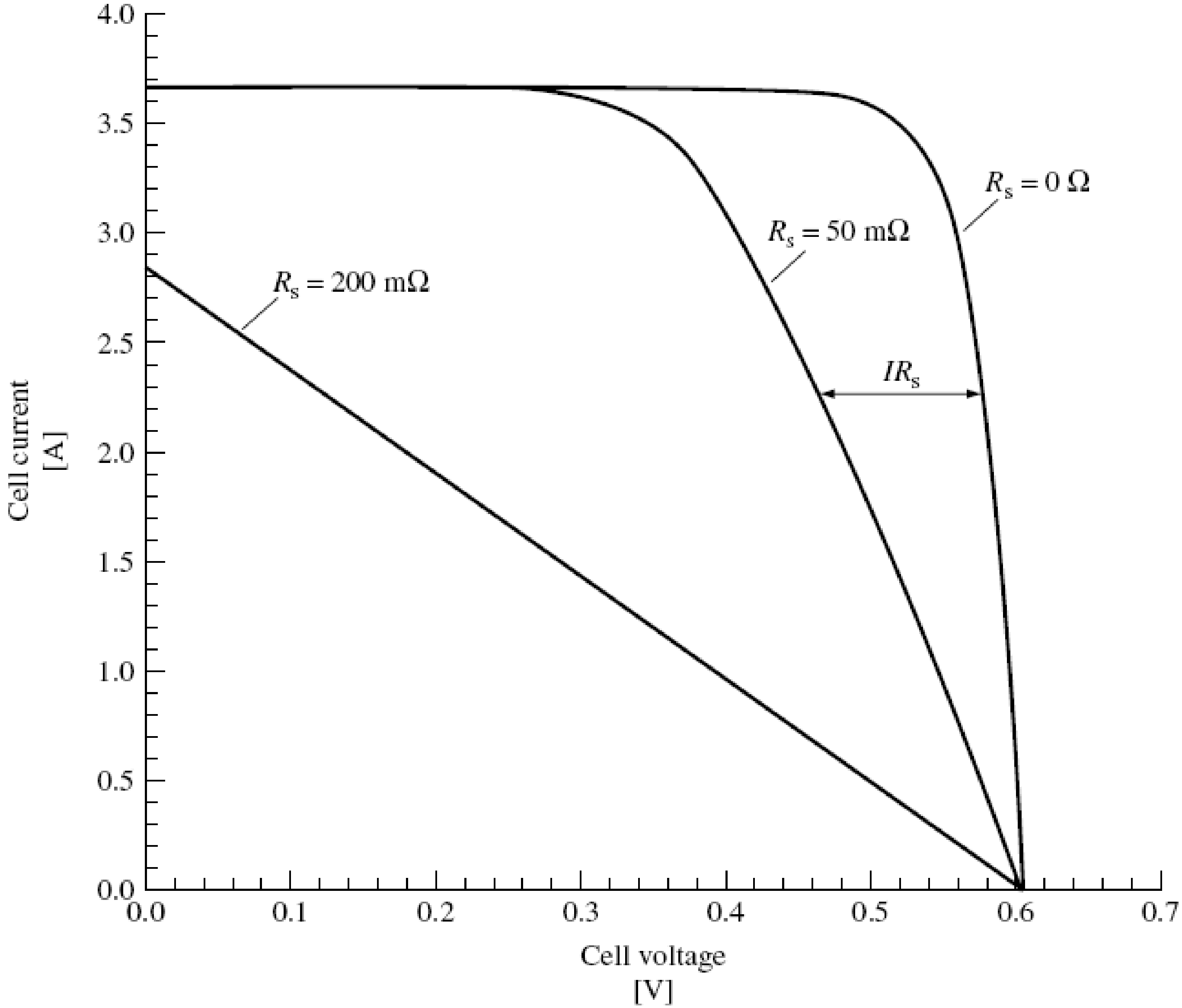
$$\eta_C = \frac{P_m}{P_{inc}} = \frac{V_m I_m}{P_{inc}}$$

The "standard" solar radiation (known as the "air mass 1.5 spectrum") has a power density of 1000 watts per square meter. Thus, a 12% efficiency solar cell having 1 m^2 of surface area in full sunlight (at solar noon at the equator) will produce 120 watts of power.

Solar cell design issues

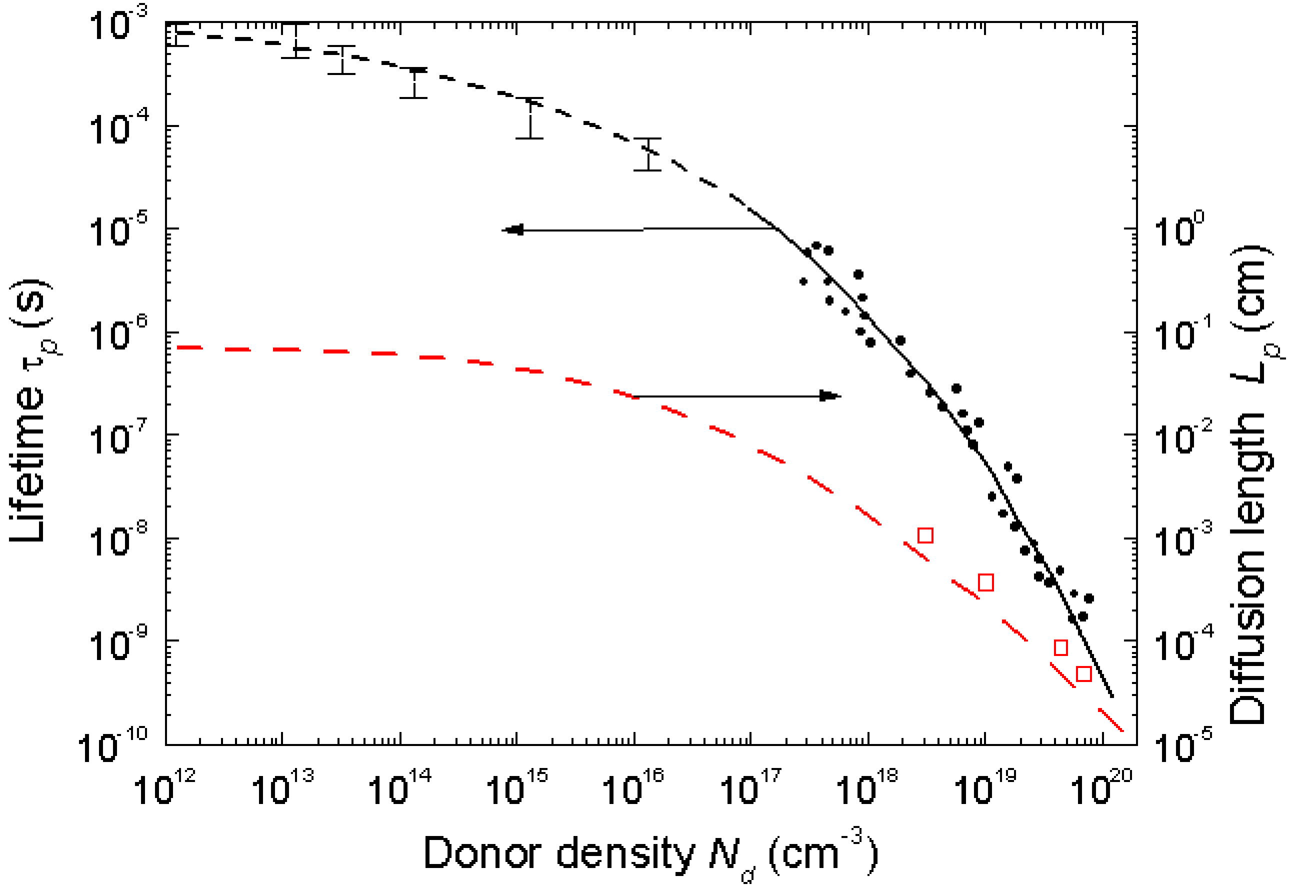


A schematic of a simple conventional solar cell.



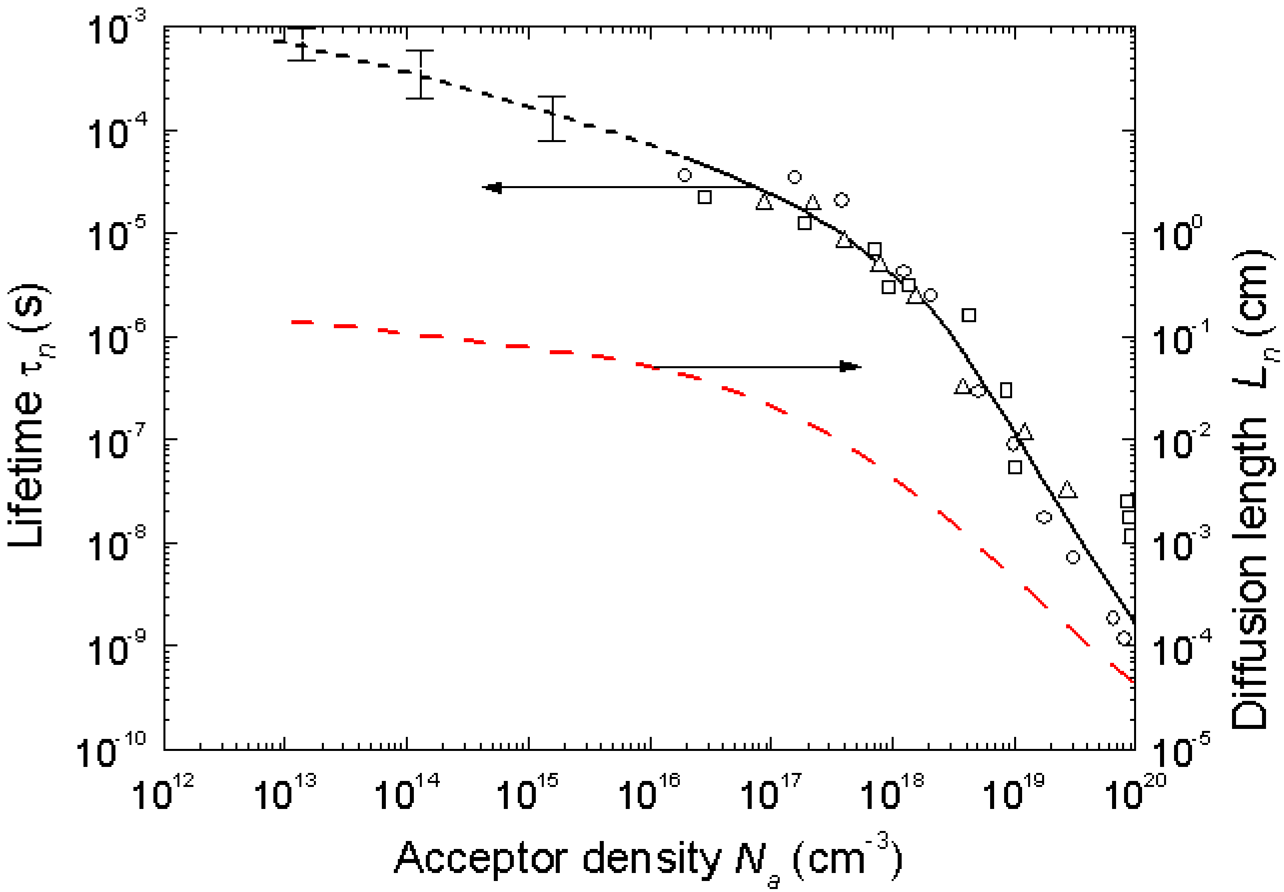
Effect of series resistance on the I-V characteristic of a solar cell

Solar cell design issues



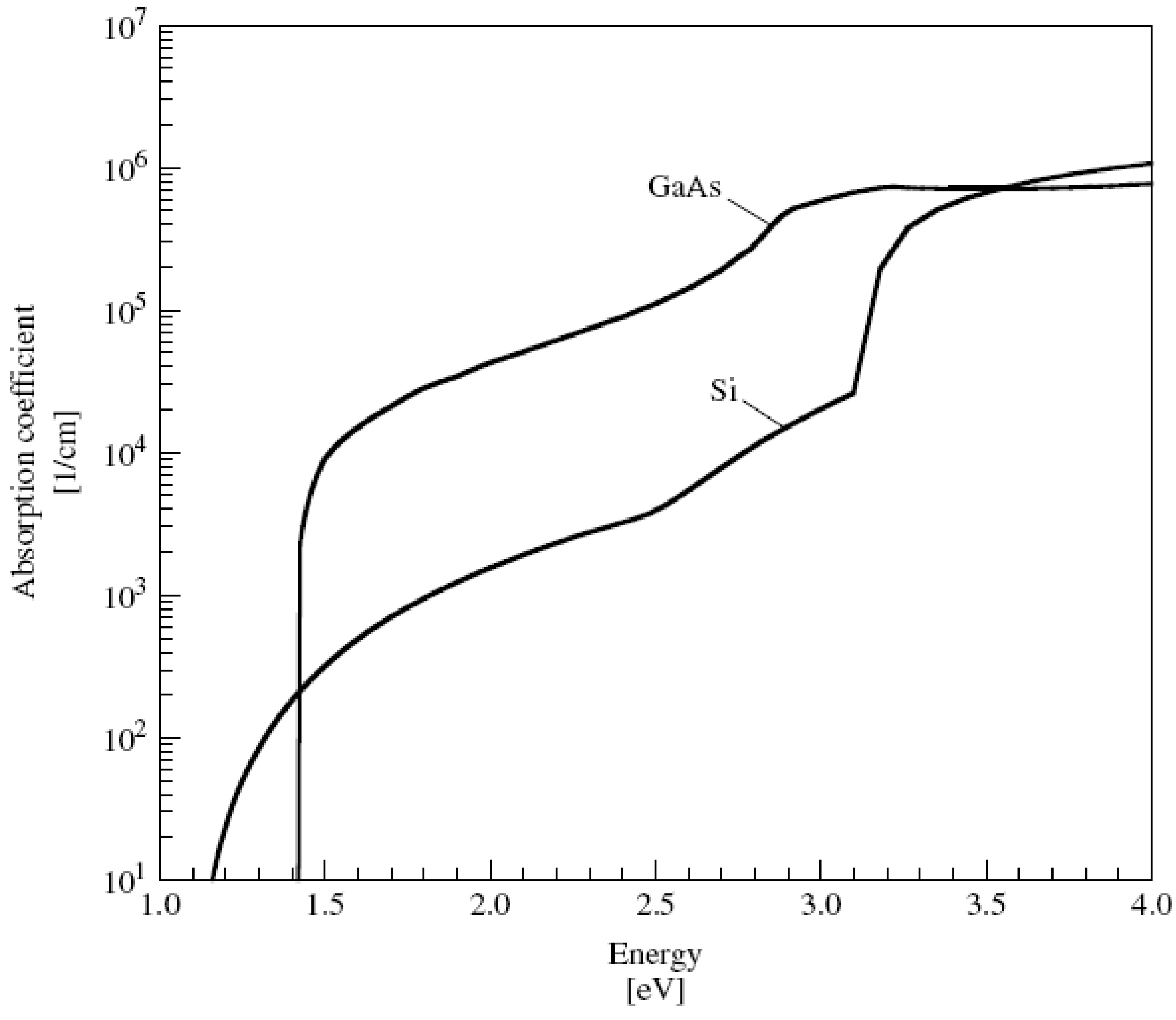
Lifetime τ_p and diffusion length L_p of holes in *n*-type Si vs. donor density. T = 300 K.

Solar cell design issues

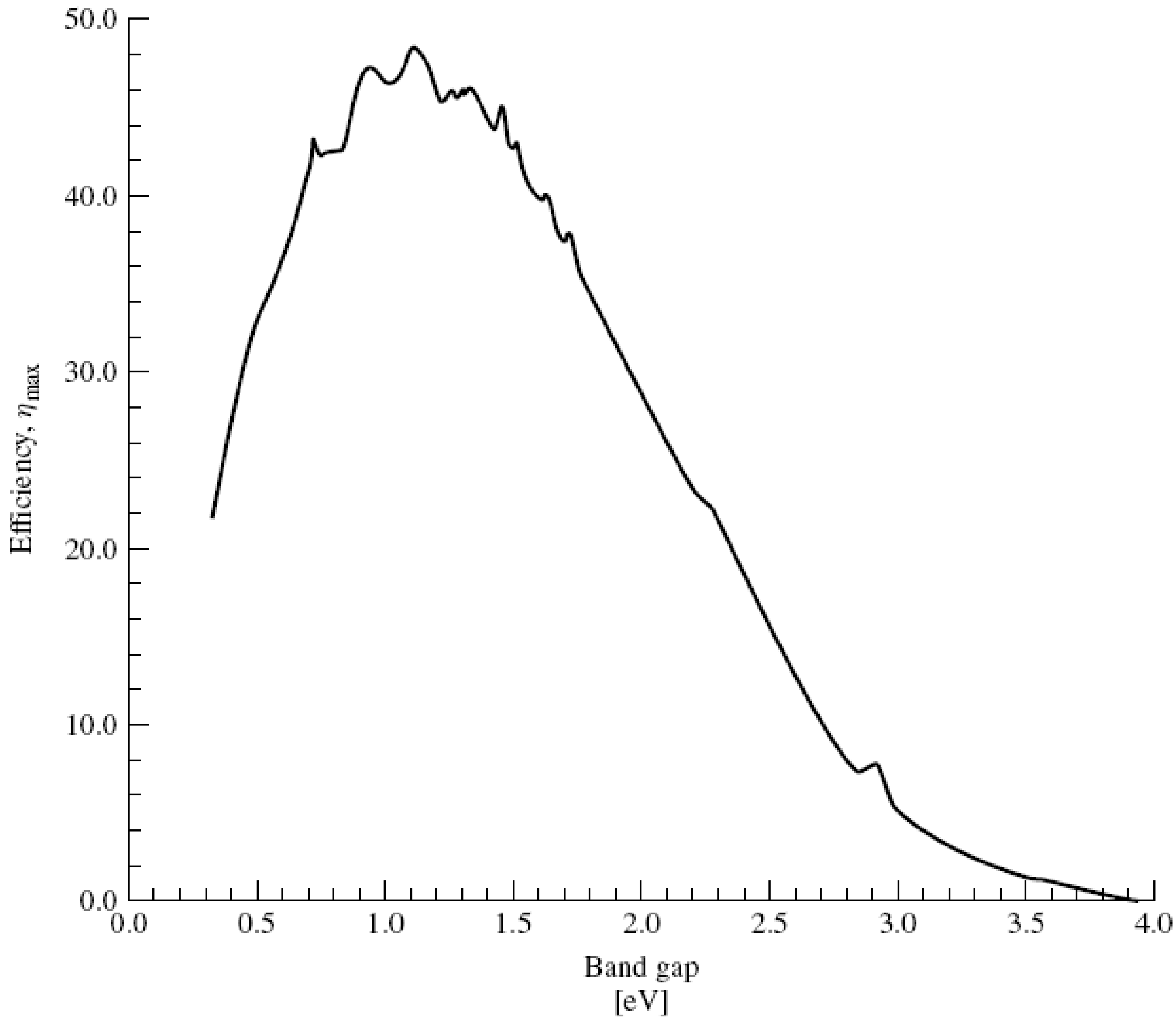


Lifetime τ_n and diffusion length L_n of electrons in *p*-type Si vs. acceptor density. T = 300 K.

Solar cell design issues



The absorption coefficient vs. photon energy



Theoretical max. efficiency as a function of semiconductor band gap

Best Research-Cell Efficiencies

www.nrel.gov/ncpv/thin_film/docs/kaz_best_research_cells.ppt