Lecture 22

Solar cells & TE coolers

Suggested reading: 5.5-5.7, 5.9-5.10

Solar cell dilemma:

1. Want enough material to absorb the light

2. Also want to be able to extract the carriers…an electron/hole pair can only travel so far in the crystal before recombination

3. Also, want to keep solar cells cheap → minimize materials usage

Solar cell dilemma:

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Have to balance absorption and:

1) Carrier diffusion (carrier response to a concentration gradient)
2) Drift (carrier response to an applied field)

1. Definition of Optical Absorption Coefficient α

$$\delta I = -\alpha I \delta x$$

α = absorption coefficient, I = light intensity, dI = change in the light intensity in a small elemental volume of thickness δx at x

Beer-Lambert Law

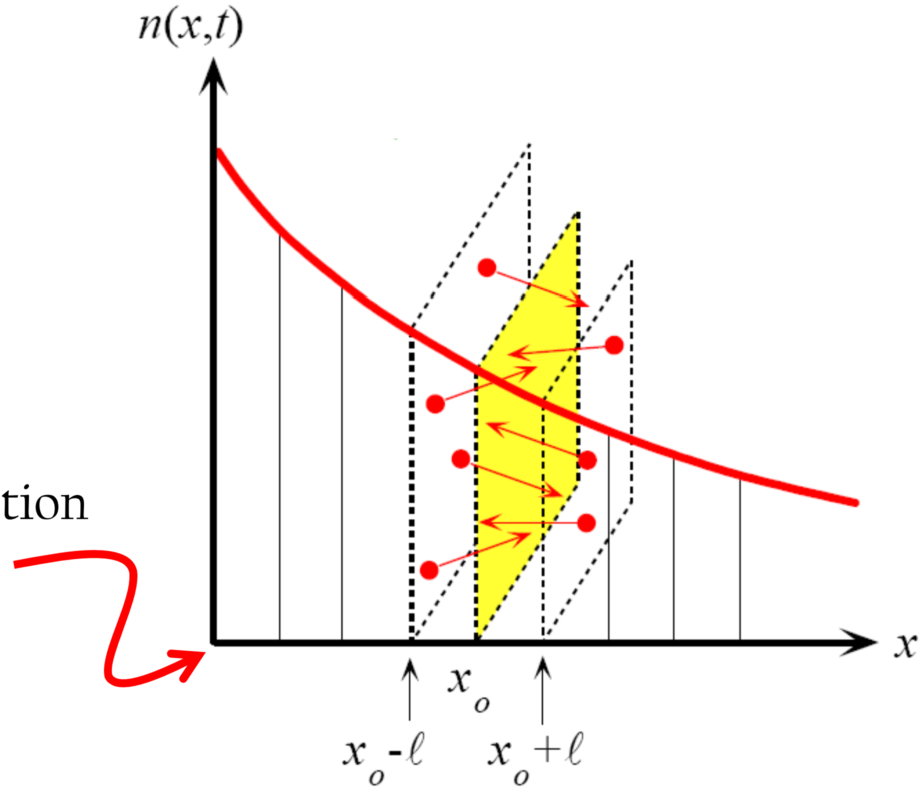
$$I(x) = I_o \exp(-\alpha x)$$

$I(x)$ = light intensity at x, I_o = initial light intensity, α = absorption coefficient, x = distance from the surface (location) where $I = I_o$. Note: Light propagates along x.

Over a distance $x=1/\alpha$, the light intensity decreases by 63% ($0.37\ I_o$)
→ absorption length (or penetration depth)

2. Carrier Diffusion

Suppose the electron concentration at some time t in a semiconductor has the profile n(x,t)



Illumination
end

There will be a net diffusion (flux) of electrons from higher to lower concentrations.

Carrier Diffusion: electrons

The net number of electrons crossing some position per unit time per unit area, Γ_e is:

$$\Gamma_e = -D_e \frac{dn}{dx}$$

“Fick’s First Law”

D_e = diffusion coefficient of electrons = ℓ^2/τ

dn/dx = electron concentration gradient

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dn/dx = electron concentration gradient

The current density due to electron diffusion is:

$$J_{D,e} = -e\Gamma_e = eD_e \frac{dn}{dx}$$

Carrier Diffusion: holes

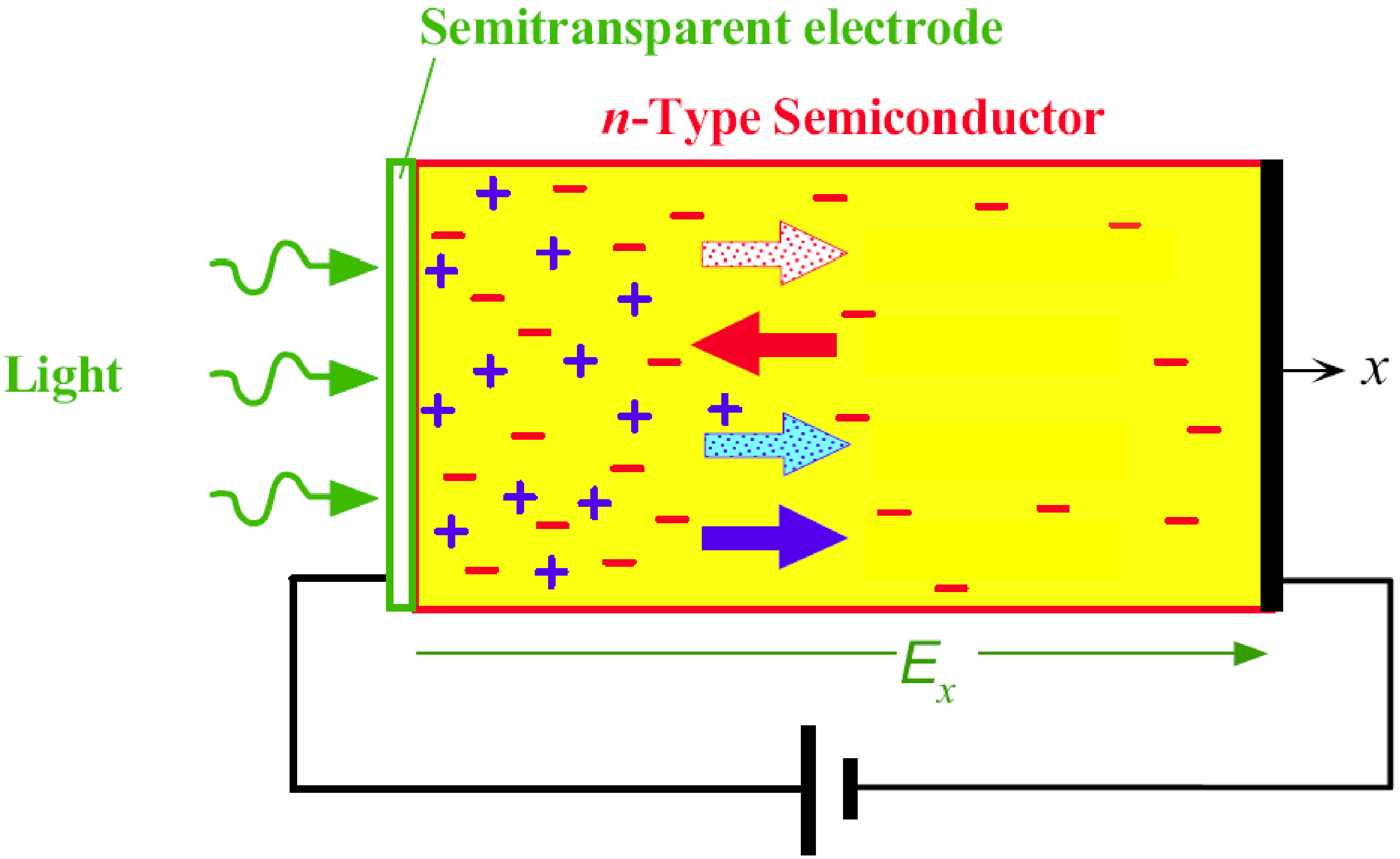
The net number of holes crossing some position per unit time per unit area, Γ_h is:

$$\Gamma_h = -D_h \frac{dp}{dx}$$

The current density due to hole diffusion is:

$$J_{D,h} = e\Gamma_h = eD_h \frac{dp}{dx}$$

When there is an electric field and also a concentration gradient, charge carriers move both by diffusion and drift.



Total Electron Current Due to Drift and Diffusion

$$J_e = en\mu_e \mathcal{E}_x + eD_e \frac{dn}{dx}$$

Total Hole Current Due to Drift and Diffusion

$$J_h = ep\mu_h \mathcal{E}_x - eD_h \frac{dp}{dx}$$

Continuity Equation:

Accounts for the total charge at a location in a semiconductor.

Rate of increase in hole concentration = Rate of photogeneration - Rate of recombination + Rate of hole concentration increase due to J_h

$$\frac{\partial p_n}{\partial t} = G_{\mathrm{ph}} - \frac{p_n - p_{no}}{\tau_h} - \underbrace{\frac{1}{e}\left(\frac{\partial J_h}{\partial x}\right)}_{=0 \text{ with uniform illumination}}$$

Steady-State Continuity Equation with $E = 0$

$$\frac{d^2 \Delta p_n}{dx^2} = \frac{\Delta p_n}{L_h^2}$$

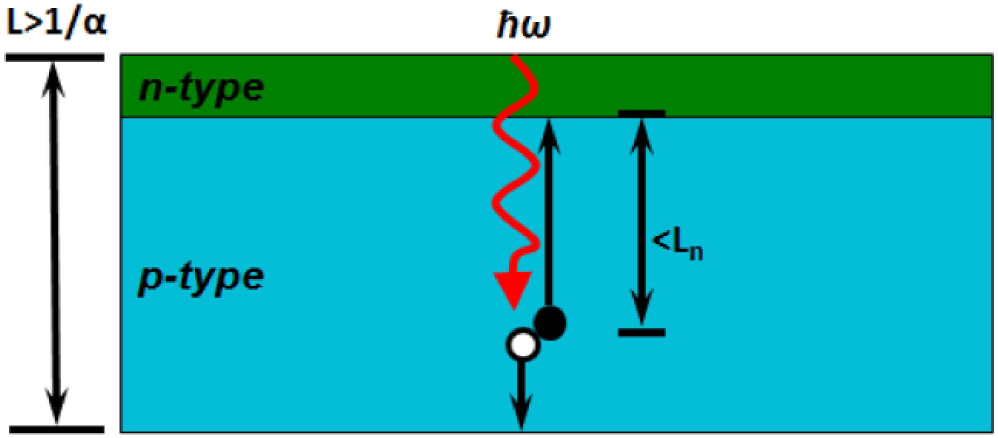
The steady state behavior of the minority carrier concentration in a semiconductor under time-invariant excitation

$\Delta p_n = p_n - p_{no}$ is the excess hole concentration, L_h = diffusion length of the holes

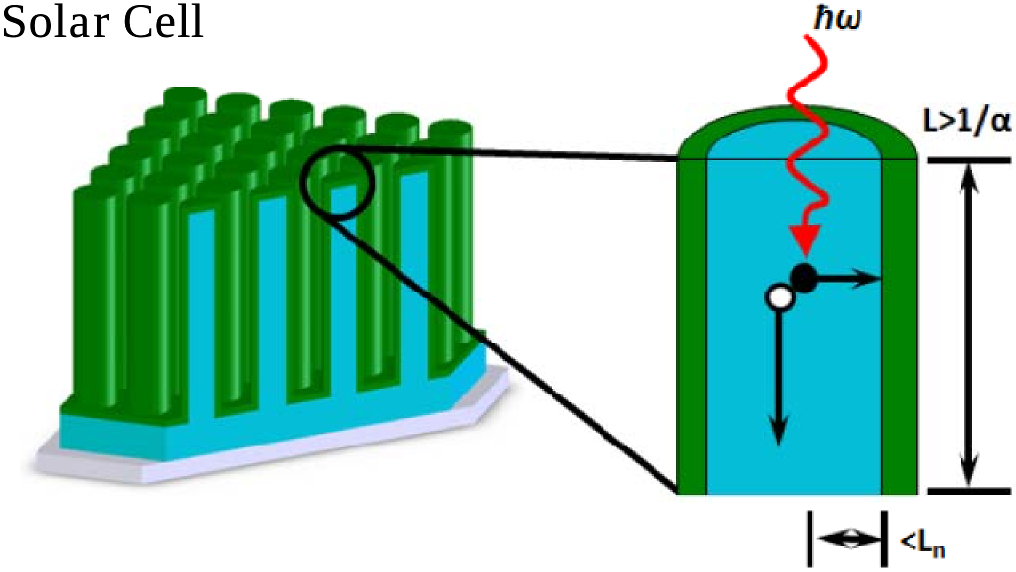
$$L_h = \sqrt{D_h \tau_h}$$

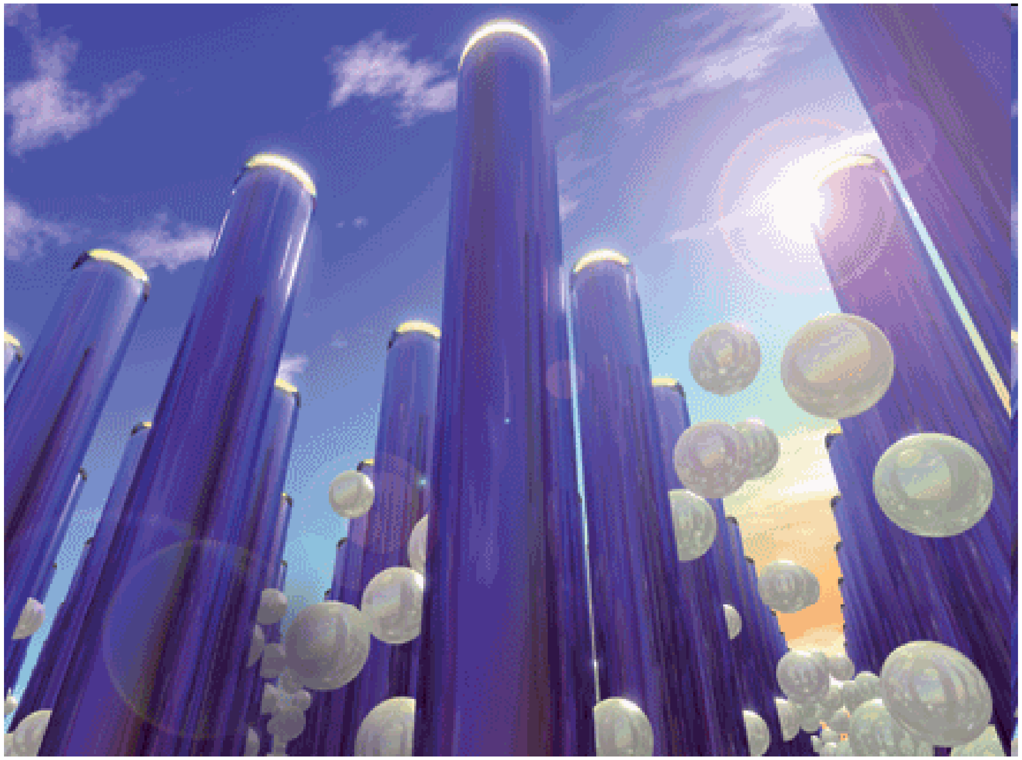
Need contacts to be within the minority carrier diffusion length in a solar cell

Planar PN Junction Solar Cell

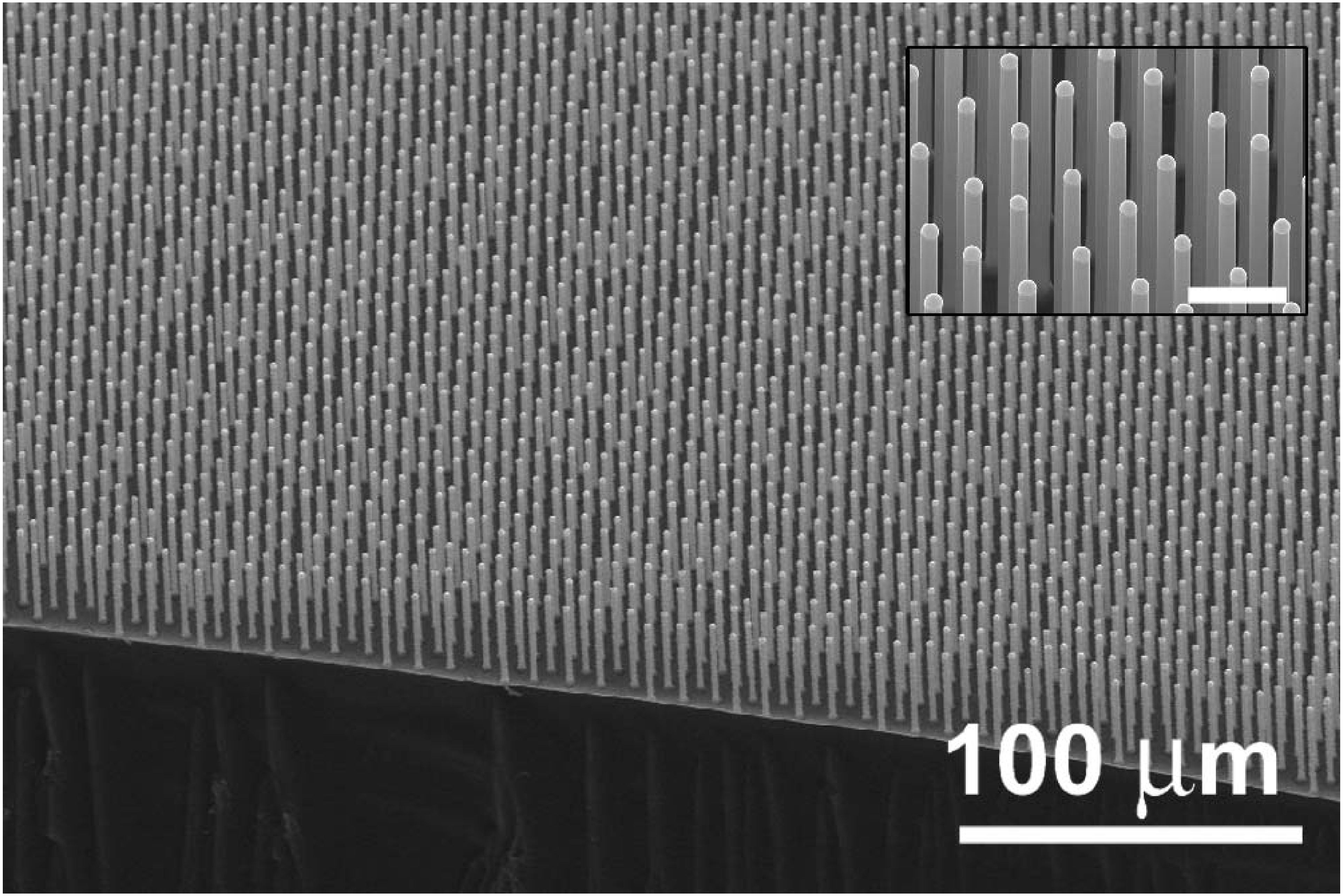


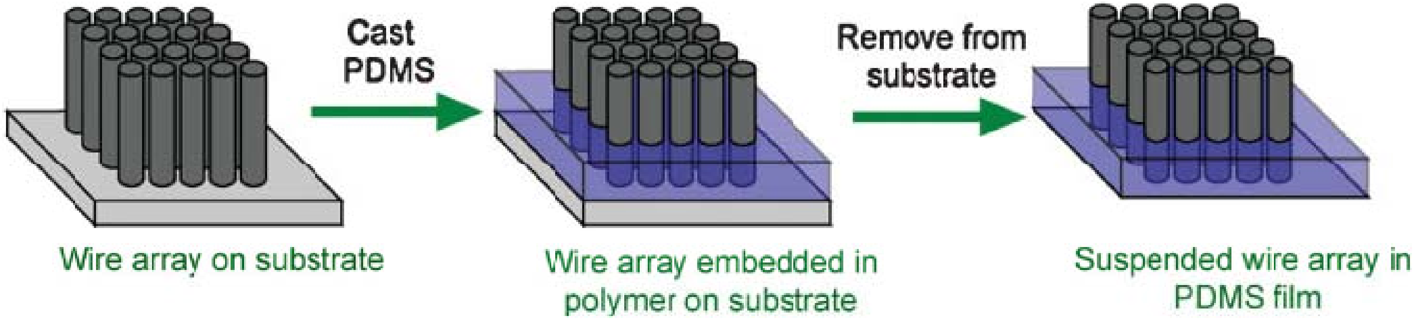
Radial PN Junction Solar Cell

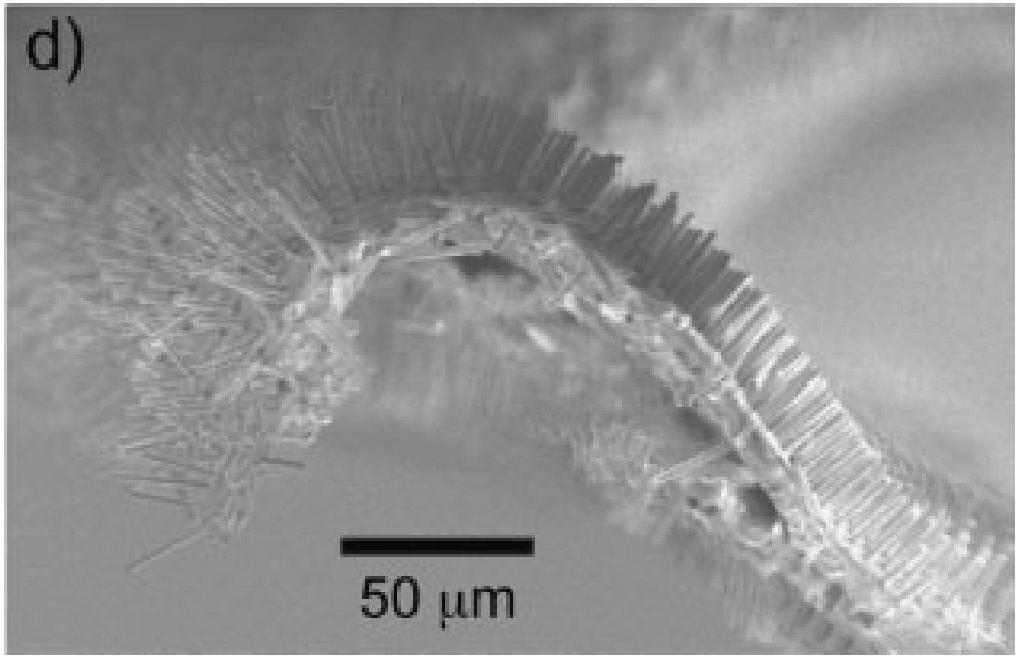




Nanorod array solar cell, from Kayes et al, Journal App. Physics (2005)



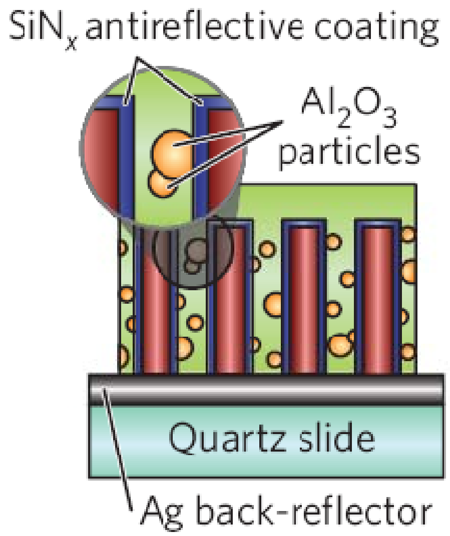


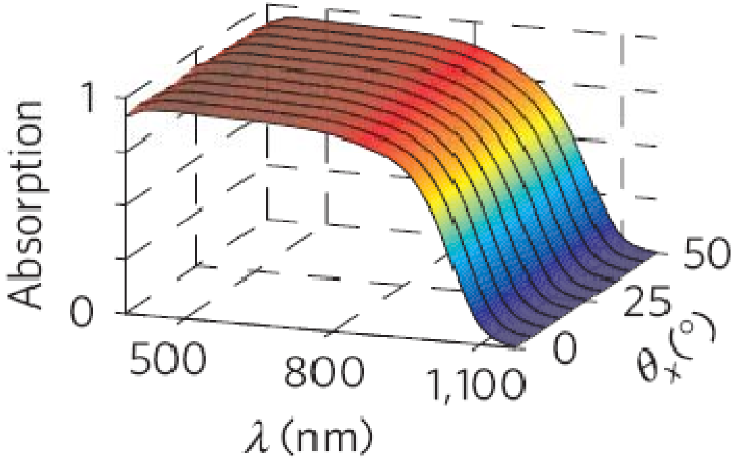


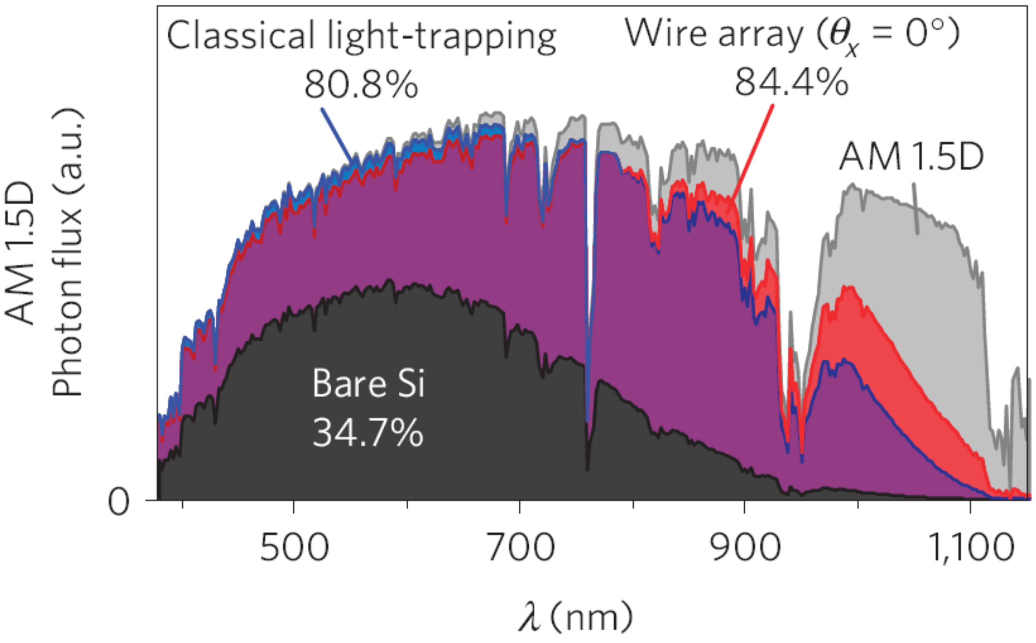
Nanorod array solar cell, from Plass, Filler, et al., Advanced Materials 2009

96% of above-bandgap light absorbed, even though only 5% of cell contains Si!

(From M. Kelzenberg, et al., Nature Materials 2010)







New solar cell could be used to make clothing

Flexible device could make solar cells far more practical for many products

By Charles Choi

TechNewsDaily

updated 3:25 p.m. PT, Wed., Feb. 17, 2010

A new solar cell can produce the same amount of energy as the best conventional solar panels while using less expensive material.

The novel **flexible** device could help make solar cells far more practical for products ranging from sunroofs to clothing, scientists say.

"It could be extremely rugged — you could roll it up, even perforate it, shoot holes in it with a gun, and it'd still operate, whereas normal crystalline silicon would just shatter like glass," said researcher Harry Atwater, an applied physicist at the California Institute of Technology at Pasadena, Calif.

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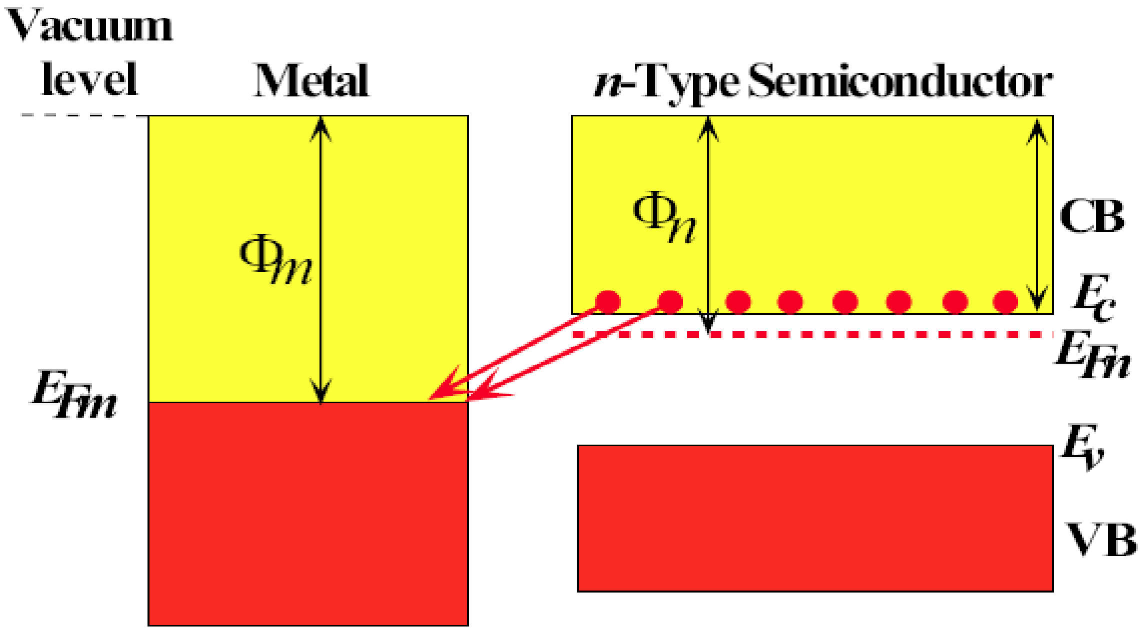
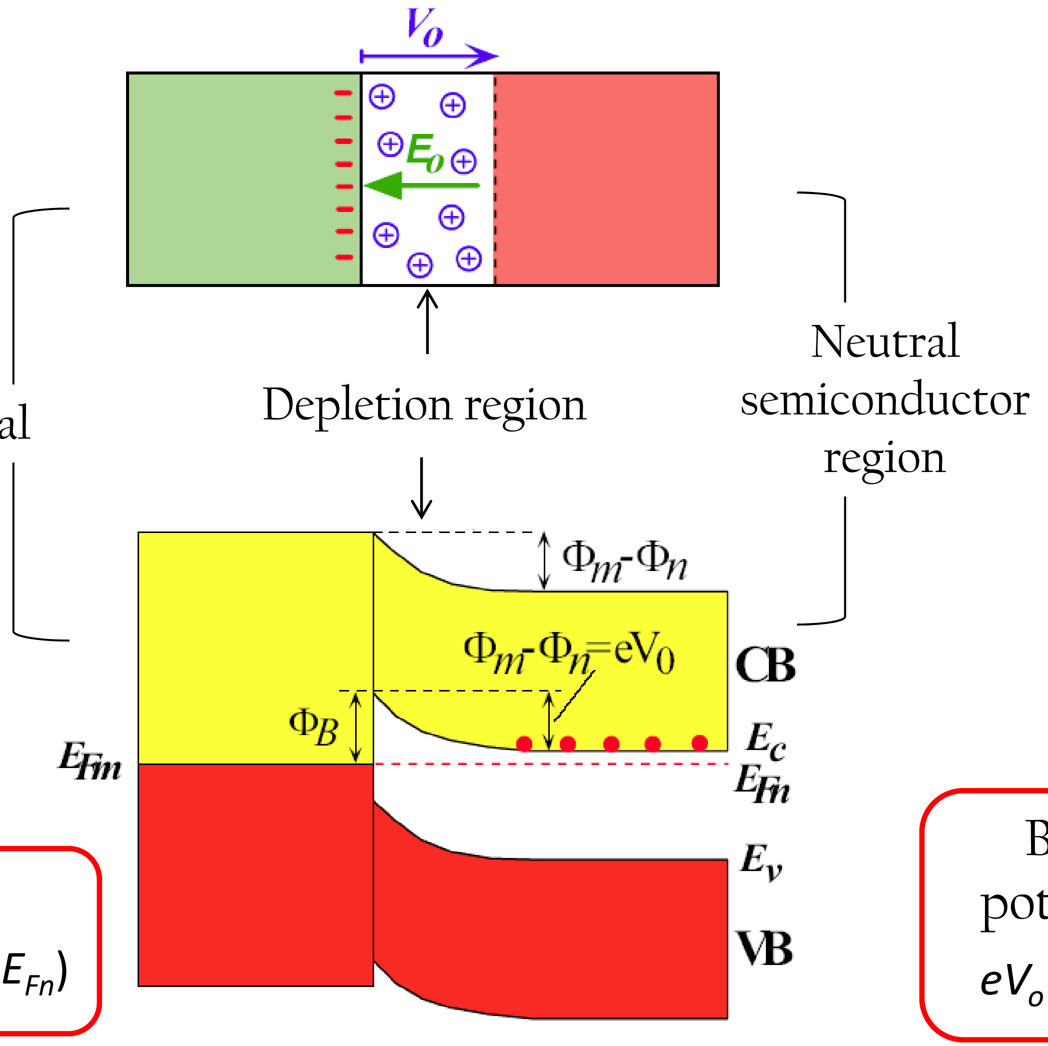
Schottky Junction Solar Cells

Consider contact between a metal and an *n*-type semiconductor with $\Phi_m > \Phi_n$.



Schottky Junction

A Schottky junction is formed upon contact of a metal and an *n*-type semiconductor with $\Phi_m > \Phi_n$.



After contact

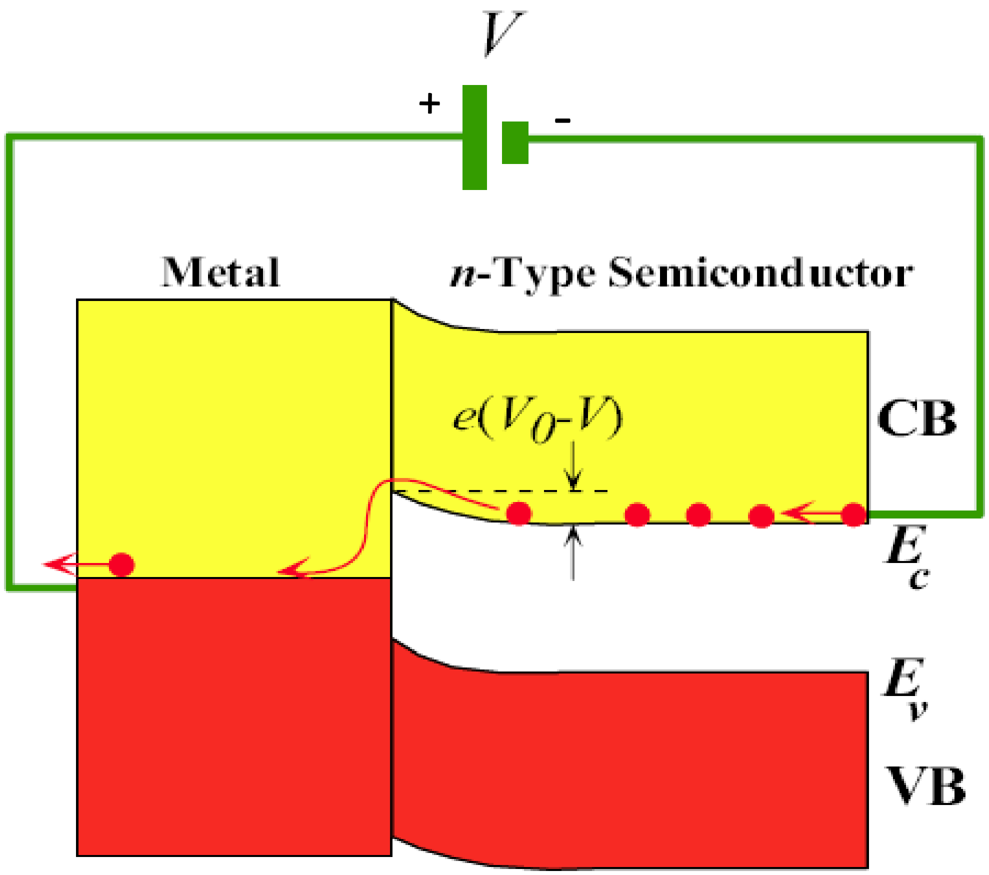
Barrier height

$\Phi_B = \Phi_m - \chi = eV_o + (E_c - E_{Fn})$

Built-in potential V_o

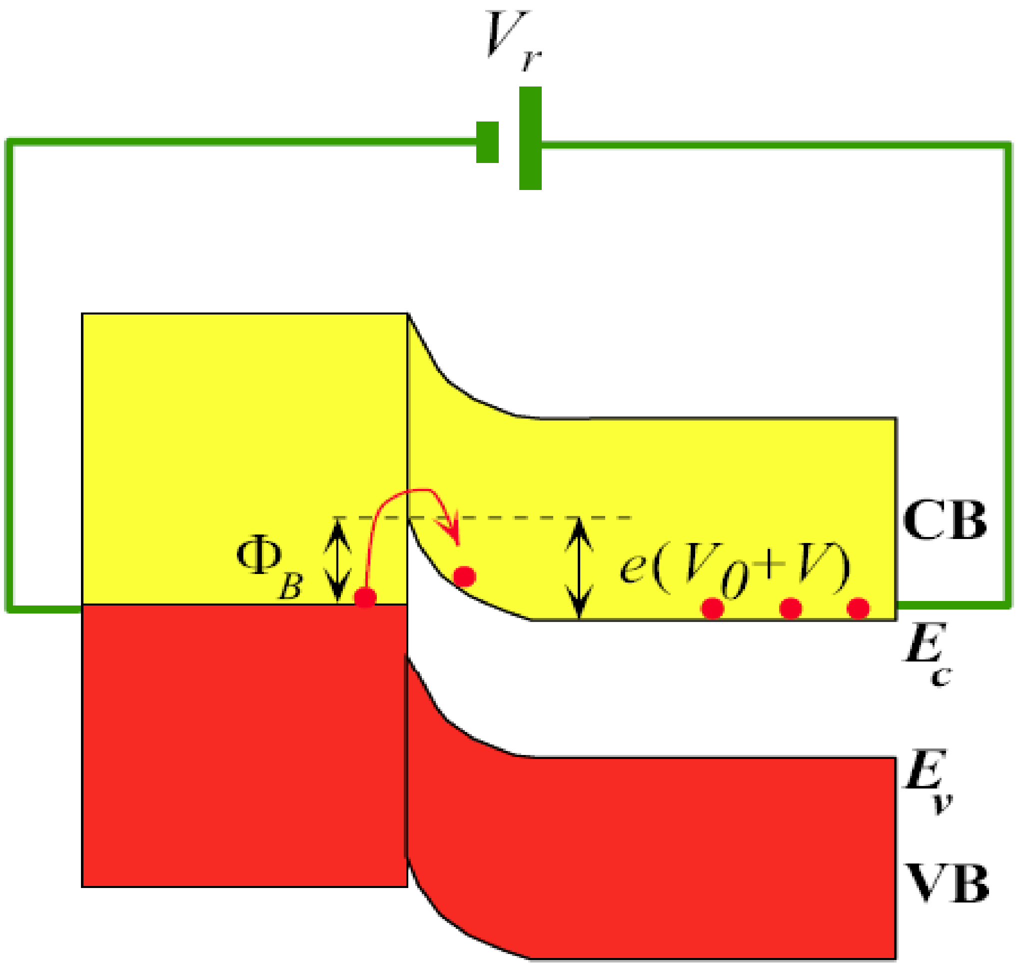
$eV_o = \Phi_m - \Phi_n$

Forward Biased Schottky Junction



Forward-biased Schottky junction. Electrons in the CB of the semiconductor can readily overcome the small PE barrier to enter the metal.

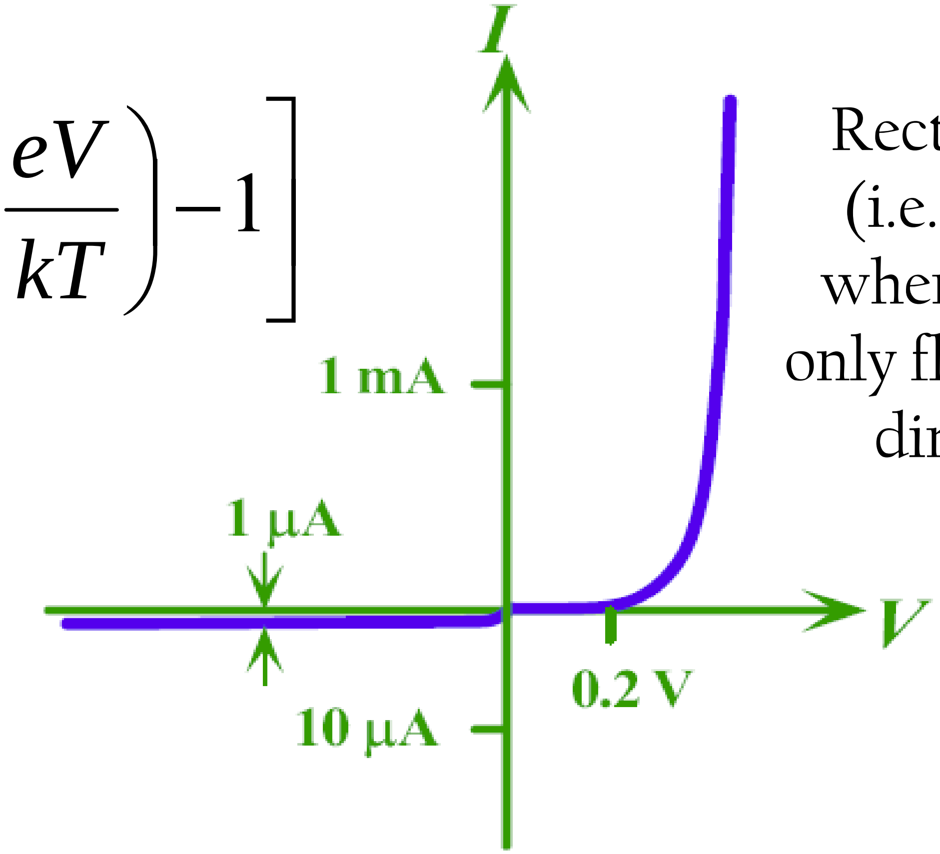
Reverse Biased Schottky Junction



Reverse-biased Schottky junction. Electrons in the metal can not easily overcome the PE barrier Φ_B to enter the semiconductor.

Schottky Junction: IV Characteristics

$$J = J_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$



Rectification!
(i.e., a diode,
where current
only flows in one
direction)

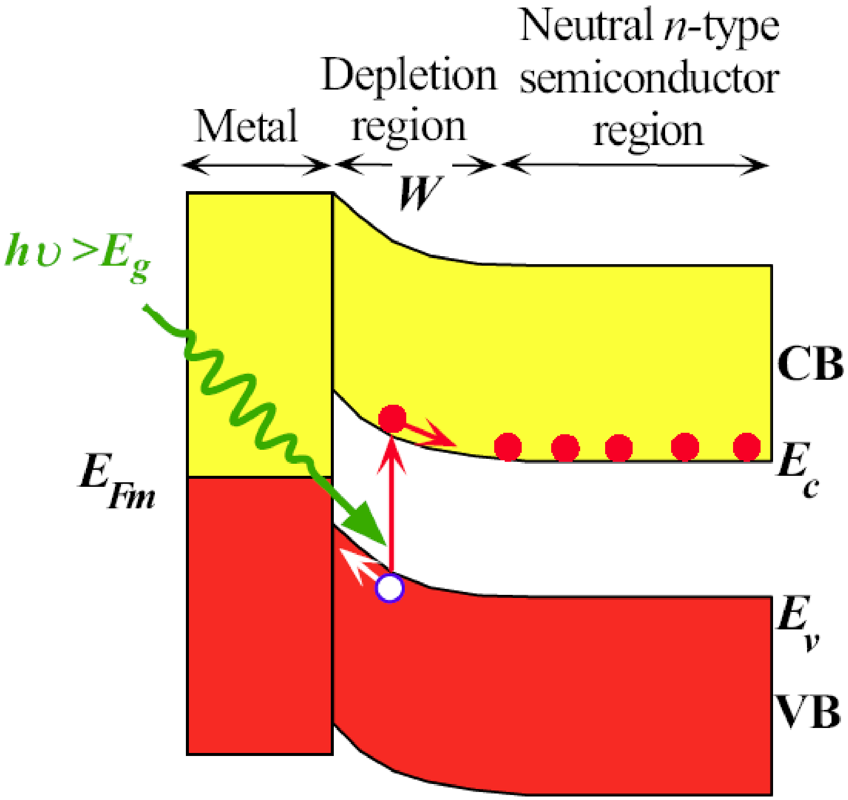
J = current density

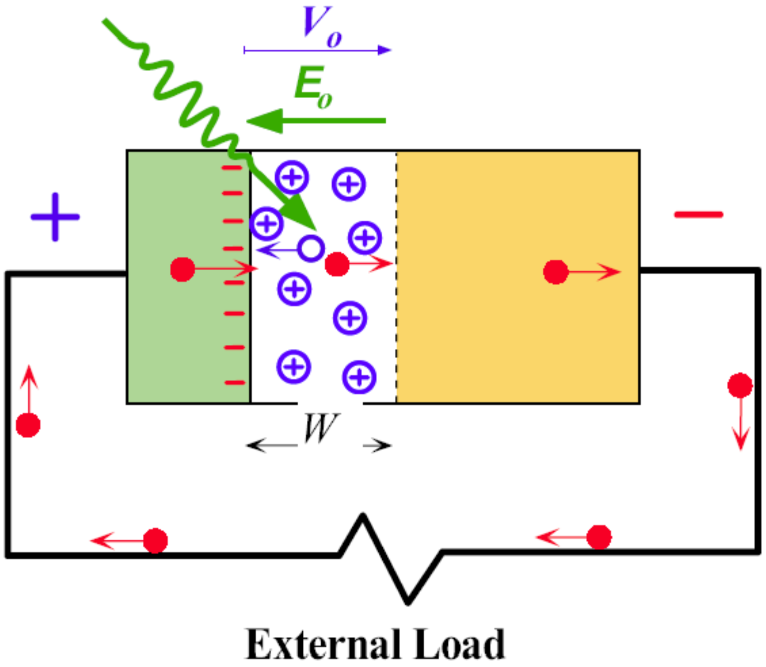
J_o = constant that depends on the metal and the semiconductor

e.g. Φ_B, V_o, and also on the surface properties

V = voltage, e = electronic charge

Schottky Junction Solar Cells

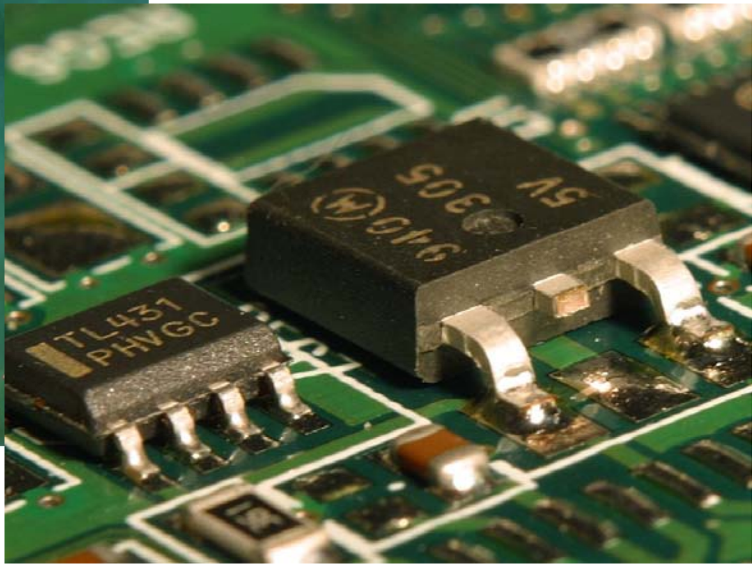




Thermoelectric (Peltier) coolers

CCDs (i.e., Hubble space telescope)

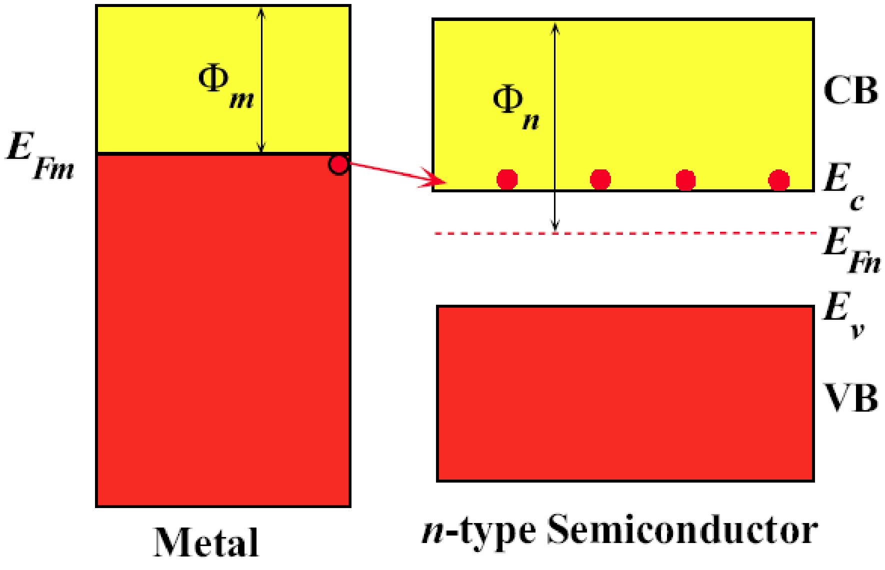
USB powered drink cooler



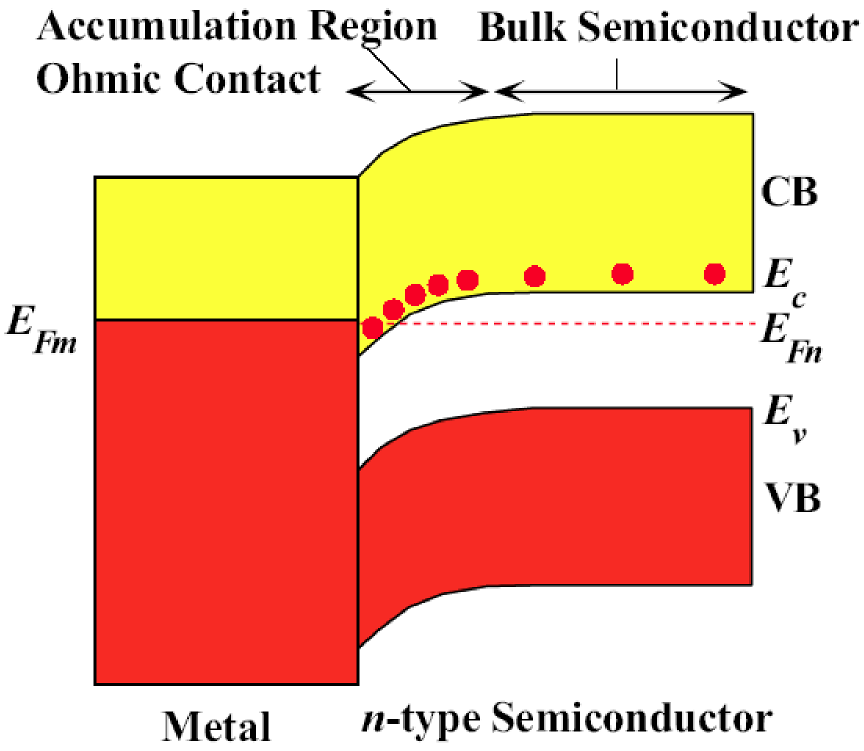
Computer chip cooling

Thermoelectric coolers rely on ohmic contacts

When a metal with a smaller workfunction than an n-type semiconductor are contacted, the resulting junction is an <u>ohmic contact</u>. Current flow will be limited only by the resistance of the semiconductor.

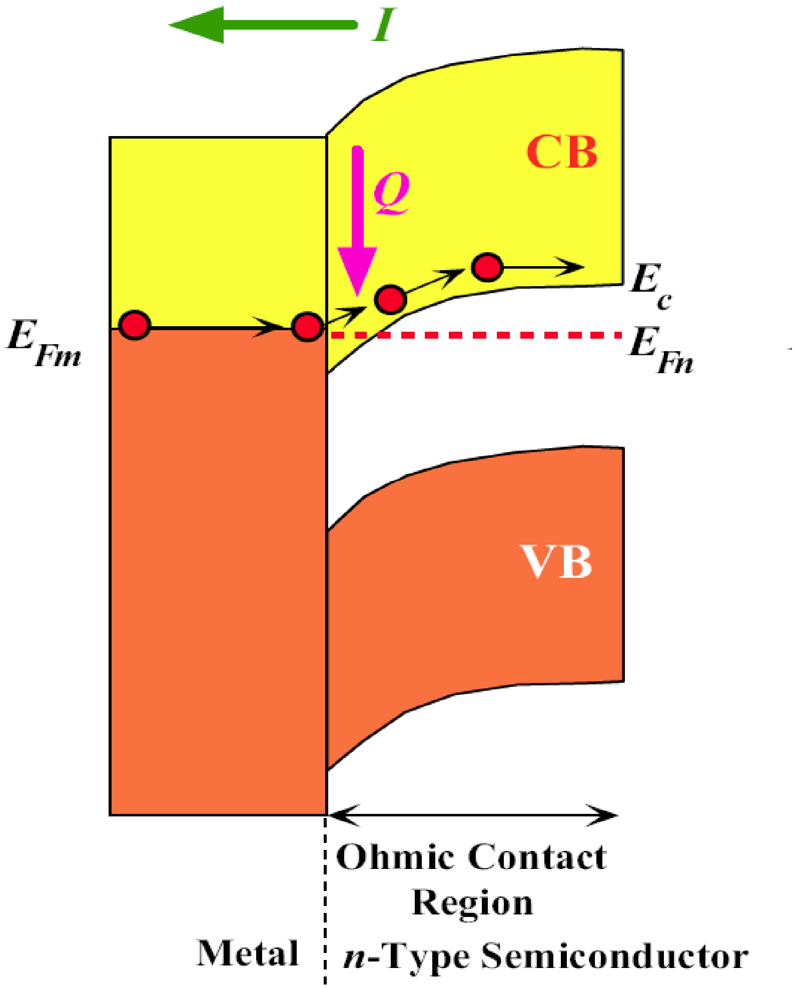


Before contact



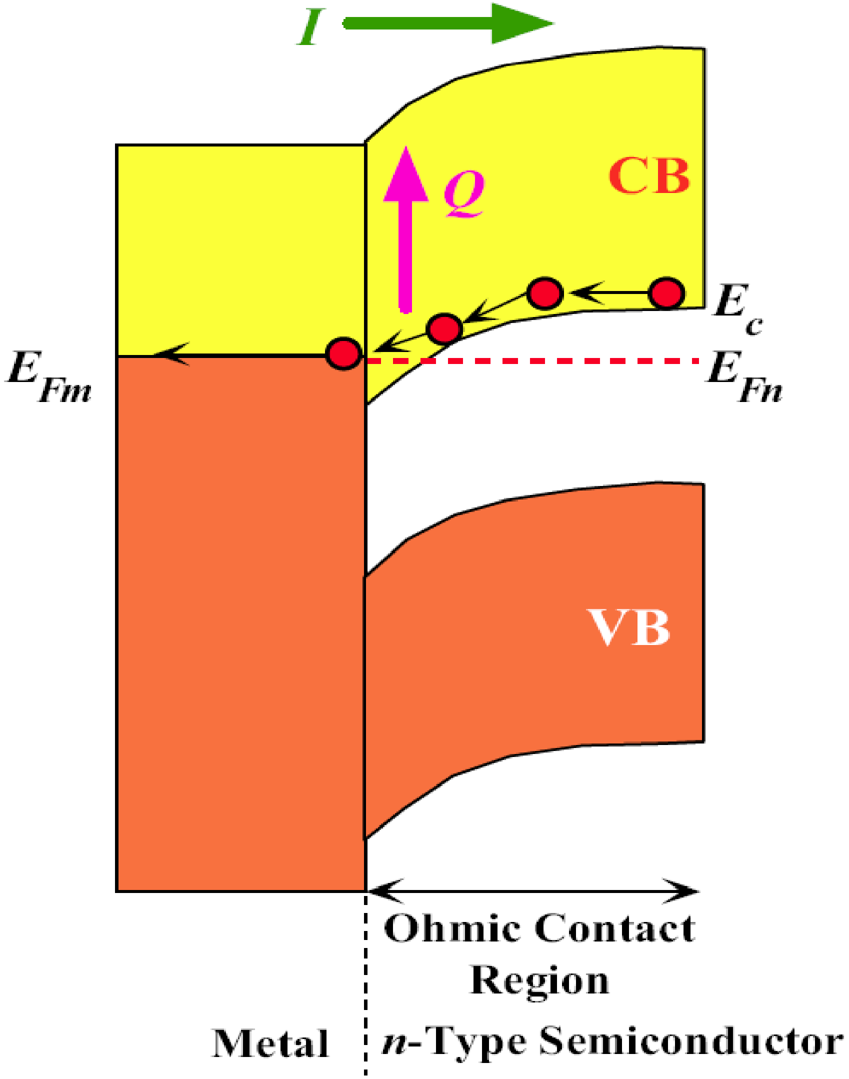
After contact

Cooling with ohmic contacts



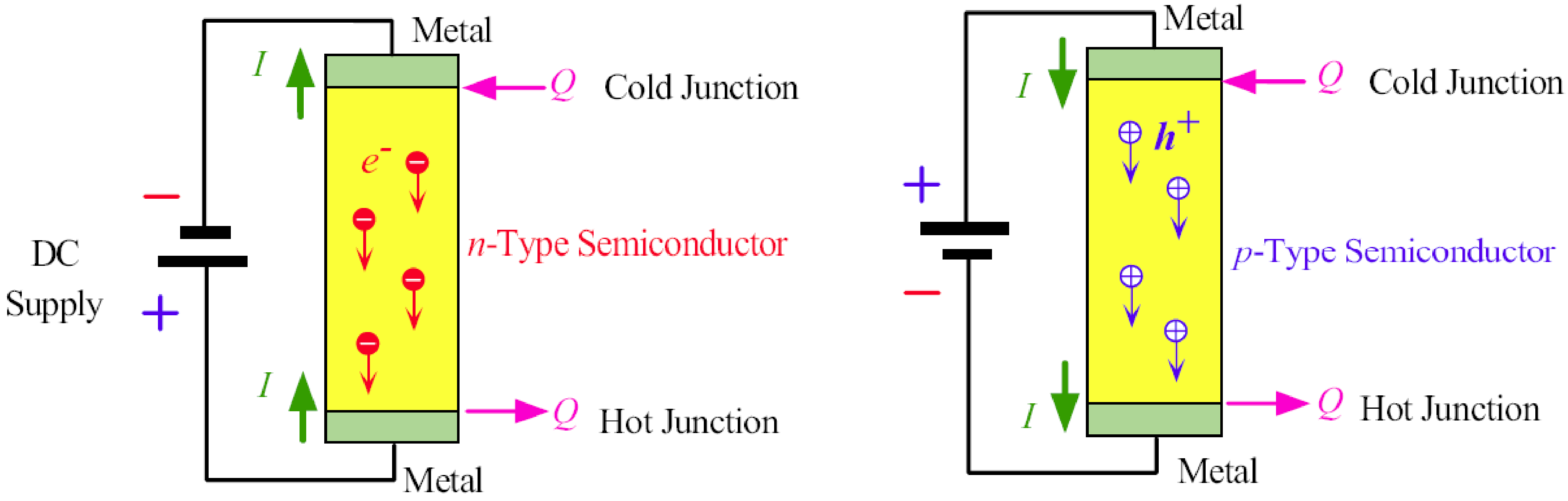
Current from an n-type semiconductor to the metal results in <u>heat absorption</u> at the junction. Recall the average energy of electrons in metals and semiconductors!

Heating with ohmic contacts



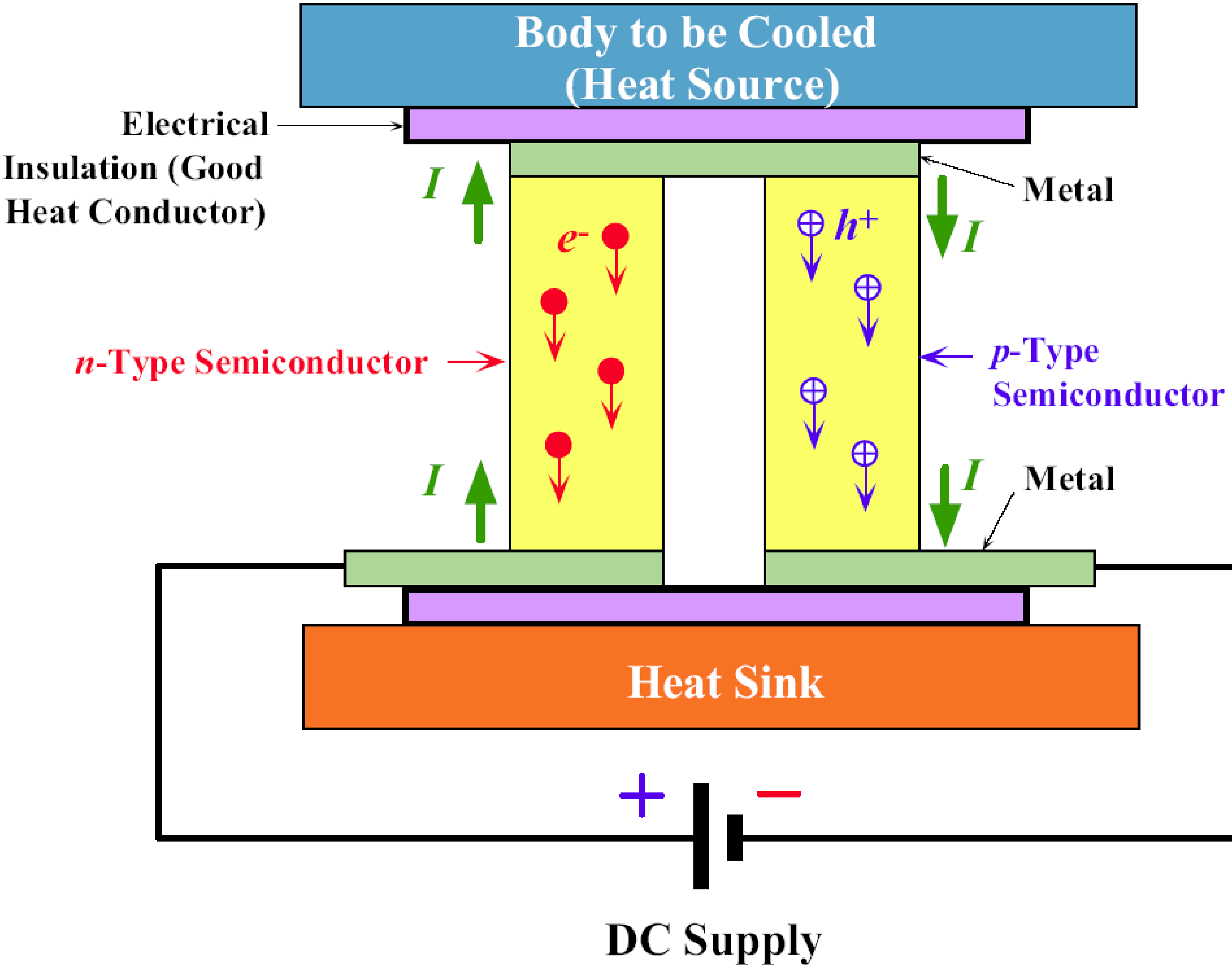
Current from the metal to an n-type semiconductor results in heat release at the junction.

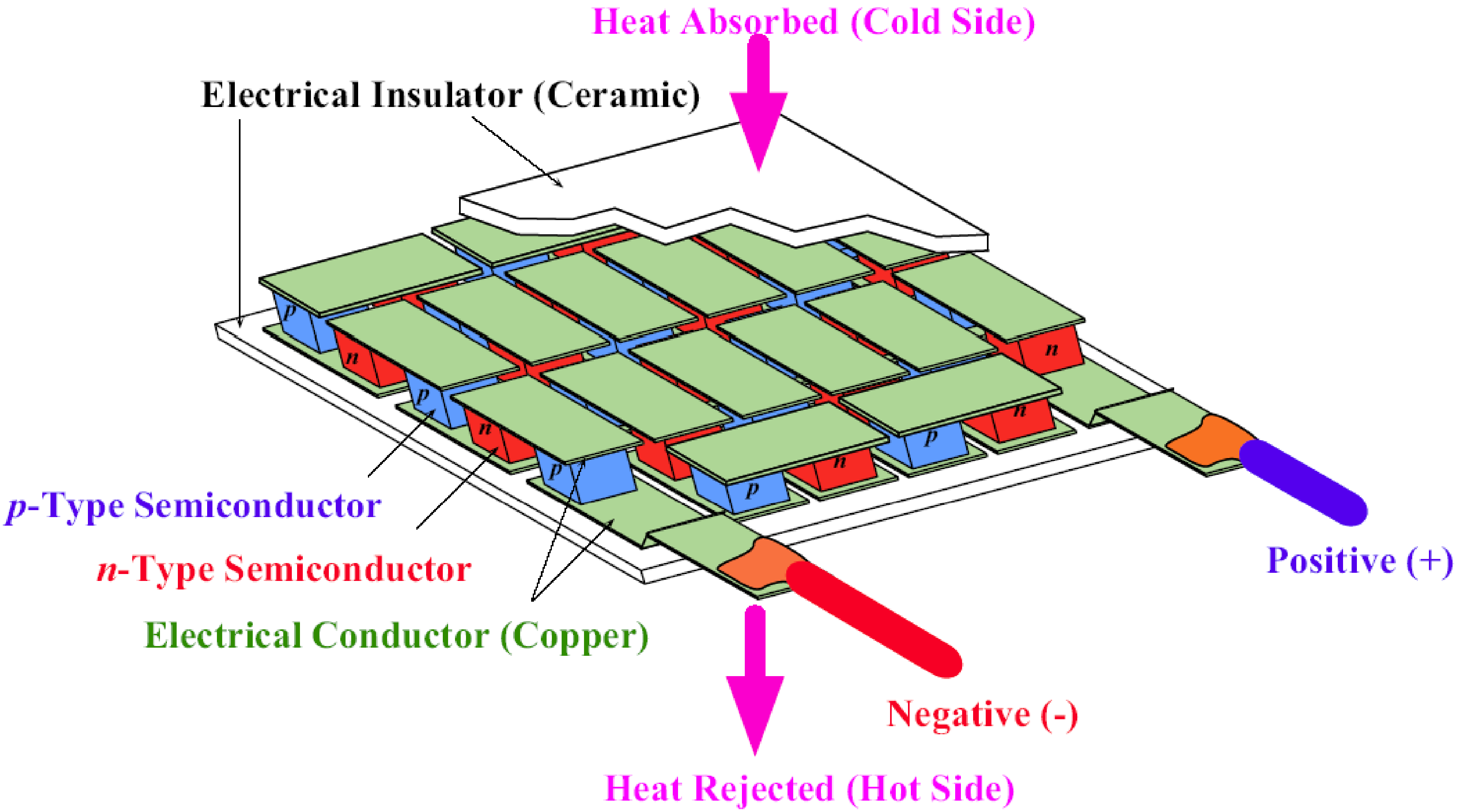
Cooling with ohmic contacts



When a DC current is passed through a semiconductor to which ohmic metal contacts have been made, one junction absorbs heat and cools (the cold junction) and the other releases heat and warms (the hot junction).

Thermoelectric (Peltier) cooler cross-section





Typical structure of a commercial thermoelectric cooler.