3.003
Principles of Engineering Practice

- One Month Review
- Solar Cells
  - The Sun
  - Semiconductors
  - pn junctions
  - Electricity

Engineering Practice

1. Problem Definition
2. Constraints
3. Options
4. Analysis
5. Solution

Tool Box (1): Wave Equation

dielectric constant and index of refraction

Wave equation

$$\nabla^2 u - \frac{1}{c_0^2}\frac{\partial^2 u}{\partial t^2} = 0$$

time and spatial variation

$$C_0 = (\epsilon_0 \mu_0)^{-1/2} = 3 \times 10^8 m/s$$

ϵ_0 = permittivity of free space

$$= \frac{1}{36\pi} \times 10^{-9} Fm^{-1} \qquad \text{(MKS)}$$

μ_0 = magnetic permittivity of free space

$$= 4\pi \times 10^{-7} Hm^{-1} \qquad \text{(MKS)}$$

n = index of refraction
= c_0/c = 1 (vacuum)
= $(\varepsilon/\varepsilon_0)^{1/2}$ (in a material)

$$\epsilon_0 \mu_0 C_0^2 = 1$$

Tool Box (2): Harmonic Oscillator

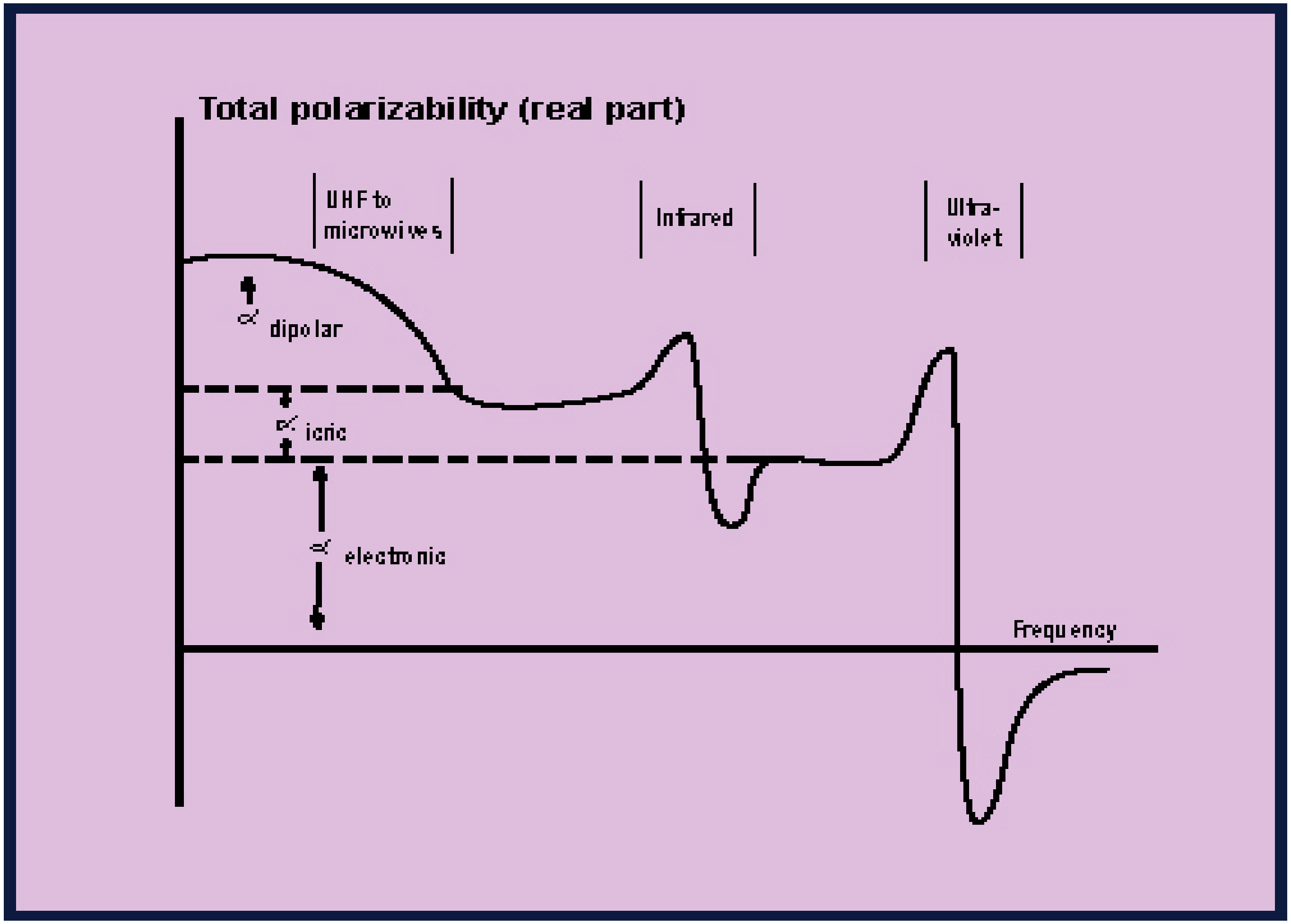
absorption and dispersion

Dynamic Relation (time dependent) between P(t) and E(t)

$$\bar{E}(t) = a_1 \frac{d^2\bar{P}}{dt^2} + a_2 \frac{d\bar{P}}{dt} + a_3\bar{P}$$

accel vel x

Polarizability, Dielectric Constant, Refractive Index



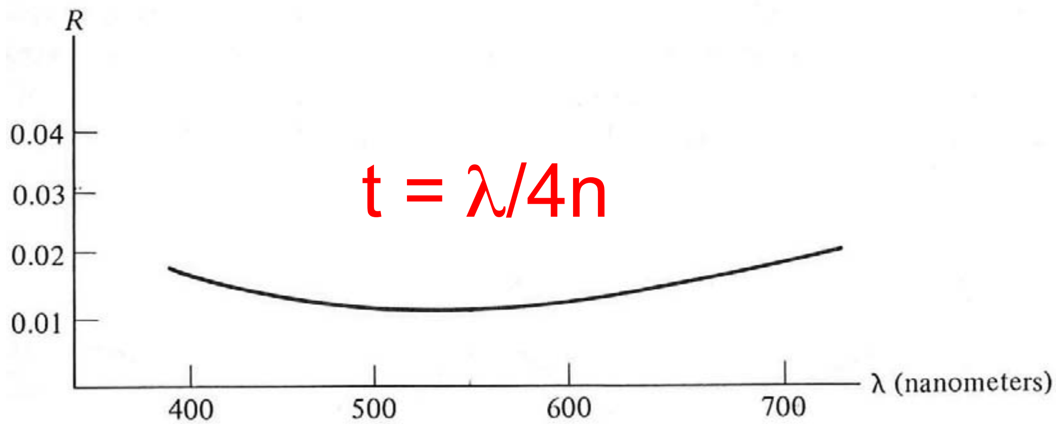
Anti-Reflection Coating Design

- Set R=0

$$n_1 = (n_0 n_2)^{1/2}$$

(index of middle layer is geometric mean of other two indices)

- Sensitivity analysis: f(λ,t,n)



The Solar Cell

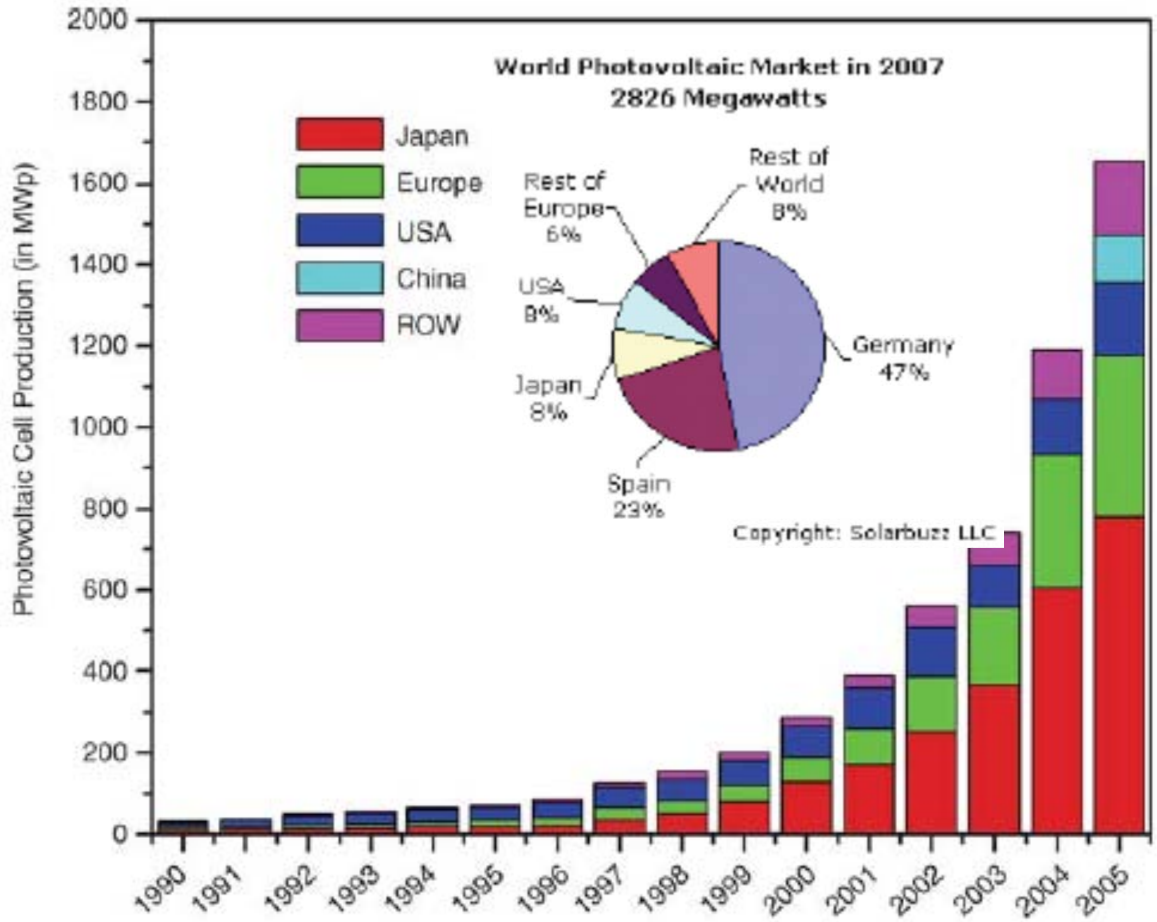
1) Principles of operation
2) Relevant performance metrics
3) Design for performance
4) Design for manufacturing
5) Design for application
6) Scale of production

Environmental and Market Driving Forces for Solar Cells

Greenhouse Gases (g/ kWh of CO_2 equivalent)

Coal	900
Oil	850
Natural Gas	400
Biomass	45
PV (Bulk Si)	37
PV (Thin Film)	18
Nuclear	24
Wind	11

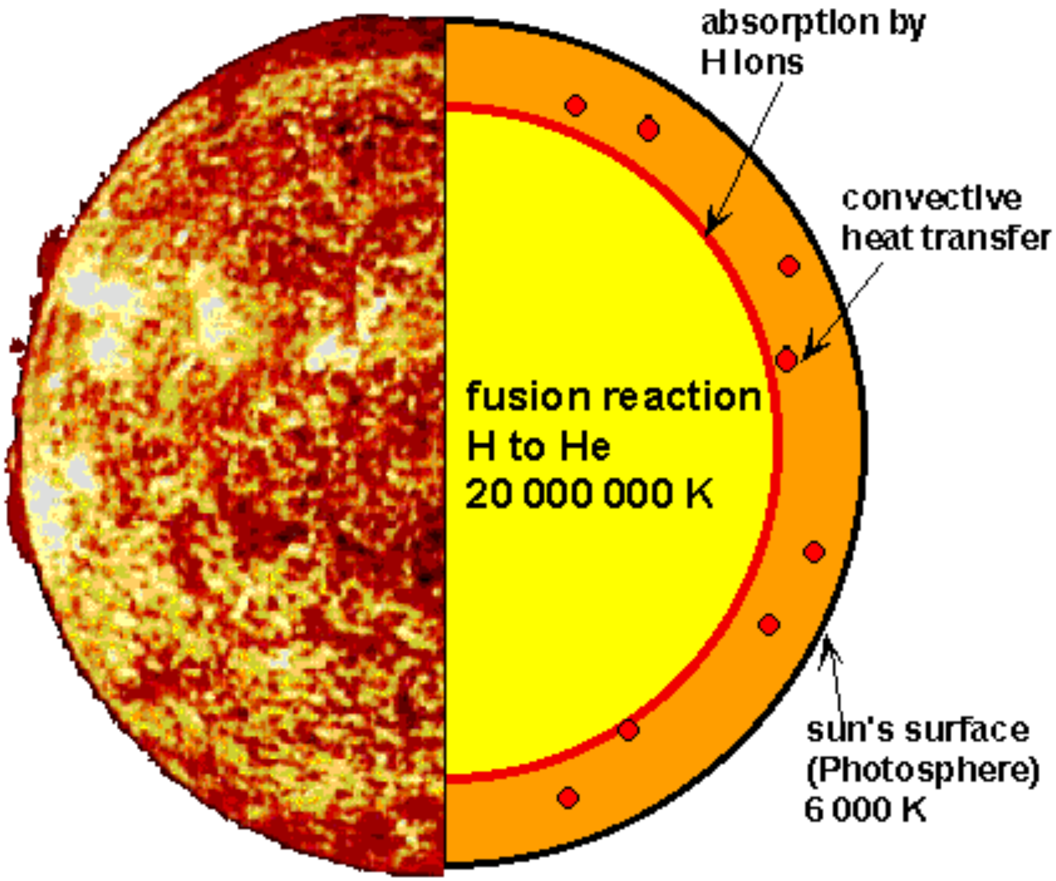
V. Fthenakis & H.C. Kim, Brookhaven National L
W. Beckman, University of Wisconsin-Madison.



Courtesy of Solarbuzz LLC. Used with permission.

- Solar cells are environmental friendly energy sources.
- Solar electricity generation was 2.8 GW power in 2007 (1.8 GW in 2006).
- World's market for solar cells grew 62% in 2007 (50% in 2006). Revenue reached $17.2 billion. (26% growth predicted for 2009 despite recession).

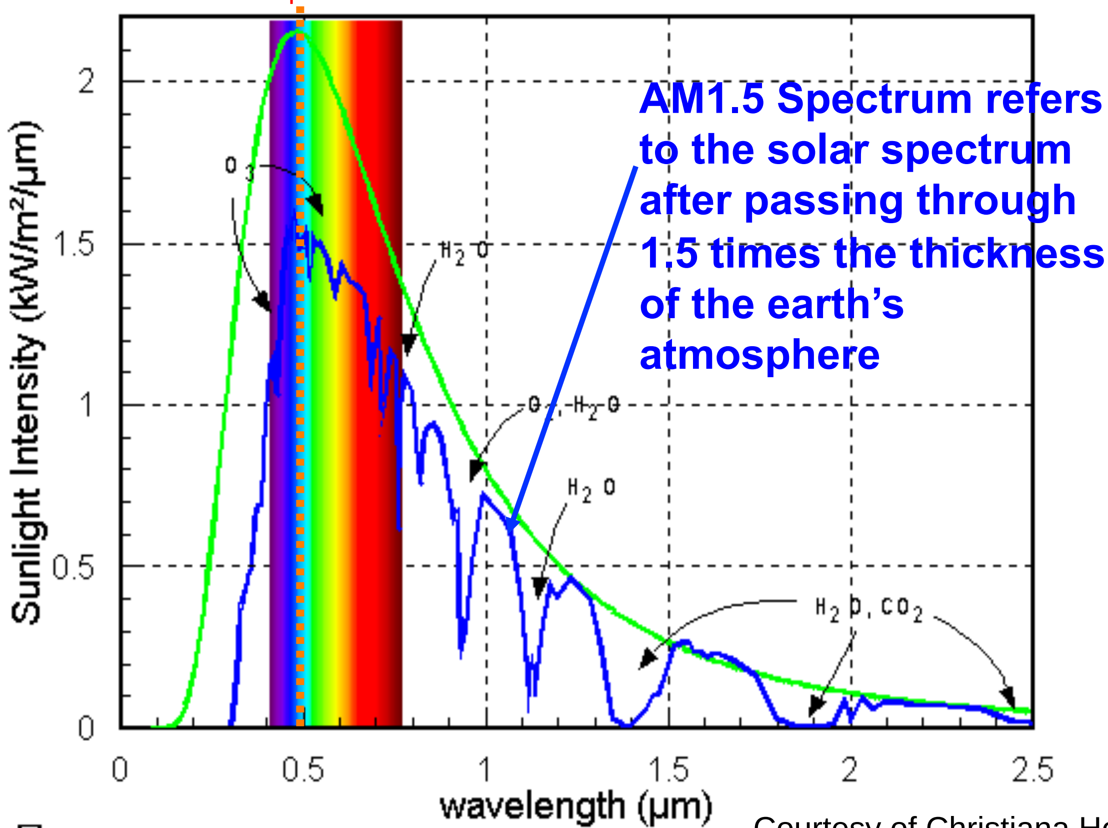
The Sun



- Sun powered by nuclear fusion. Surface temperature~5800 K
- Will last another 5 billion years!

The Solar Spectrum

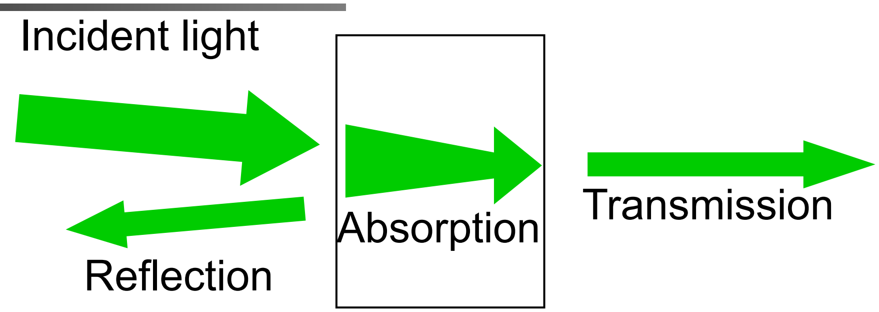
λ_{peak} (μm)=2900/T (K)~0.5 μm

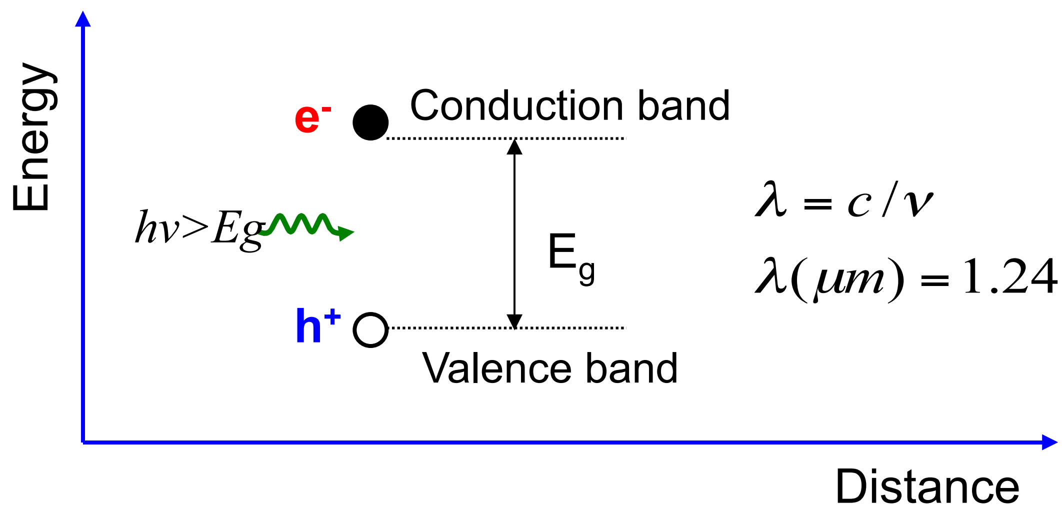


Courtesy of Christiana Honsberg and Stuart Bowden. Used with permission.

- Solar spectrum on earth is black body radiation modified by molecular absorption in the atmosphere.
- Power density ~0.9 kW/m^2 on a sunny day.
- Total energy delivered to earth~10^{18} kWh/year (8000x global energy consumption)!

Light-Matter Interaction





$$\lambda = c/\nu$$

$$\lambda(\mu m) = 1.24 / h\nu(eV)$$

Absorption (A) + Reflection (R) + Transmission (T) = 1

Absorb the incident light in order to harvest optical energy.

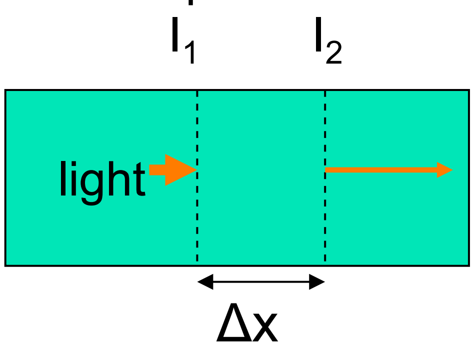
Minimize reflection helps to maximize absorption

Photon energy (hc/λ) > *band gap (E_g)* to be absorbed

Does a blue semiconductor exist?

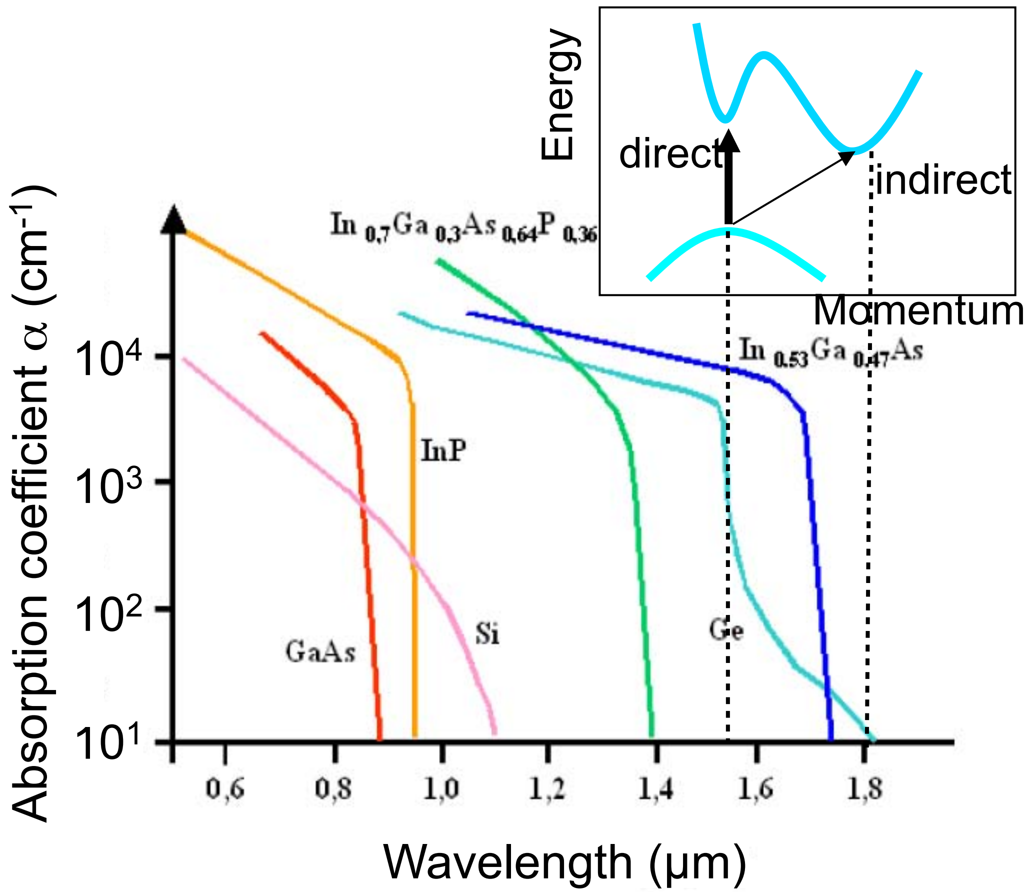
Absorption Spectra of Semiconductors

α = Absorption Coefficient



$$dI / dx = -\alpha I$$

$$I_2 = I_1 \exp(-\alpha \Delta x)$$

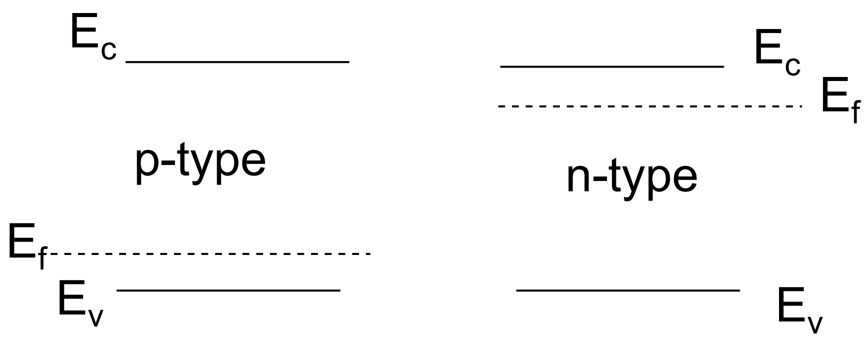


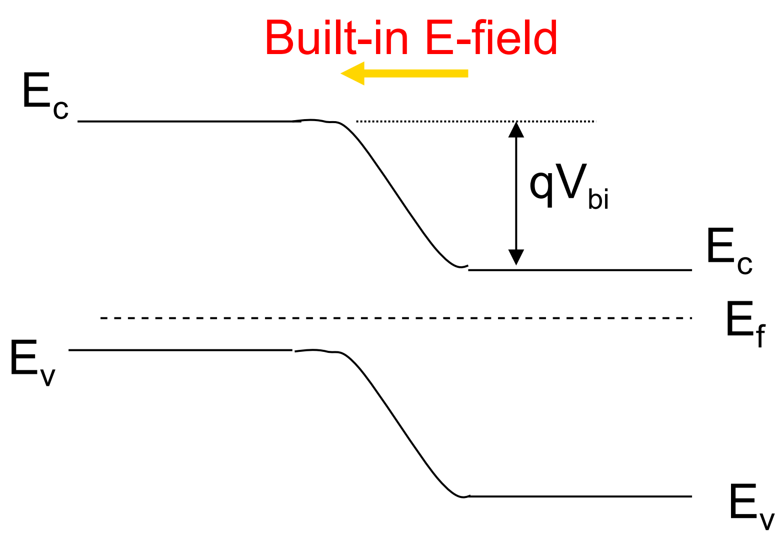
Courtesy of Helmut Föll. Used with permission.

- *Absorption Coefficient (α)* defines the material's absorbed optical power.
- *Direct gap materials* have a much higher α

Tool Box (3): The pn junction

Solar Battery Voltage



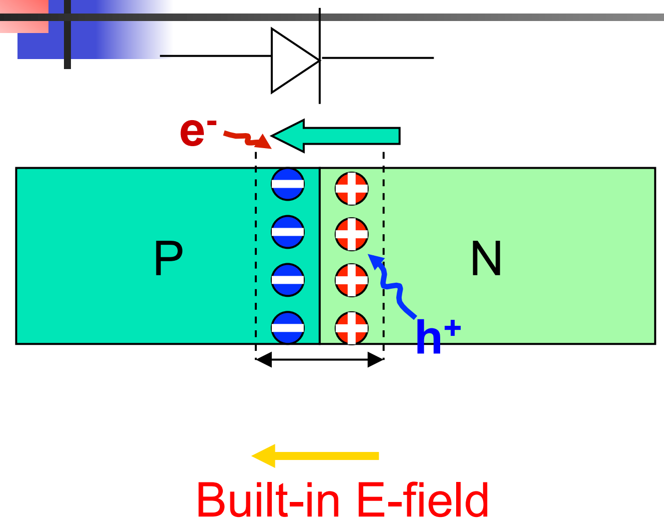


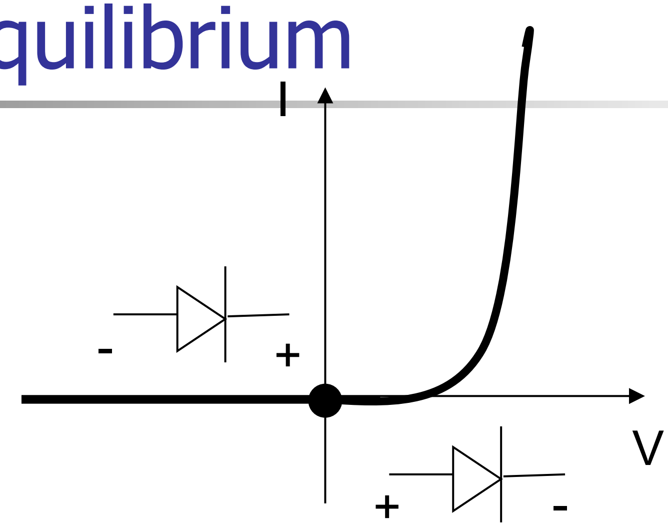
- The potential is the electrochemical potential of the electron, known as the Fermi level, E_f.
- $E_f = kT \ln (n/N_c)$
  - n = electron concentration
  - N_c = 'density of states'

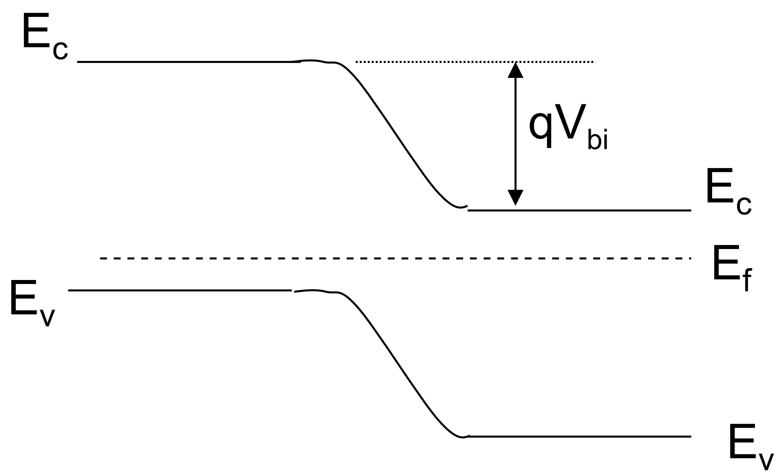
    = empty states at E_c

When two dissimilar materials contact, charge flows to equalize the chemical potential. This charge exchange creates the voltage to drive current under illumination.

P-N Junction at Equilibrium







Reverse current:

Any minority carriers (e^- in p-type semiconductor or h^+) can drift under the built-in electric field and induce a reverse current $-I_0$

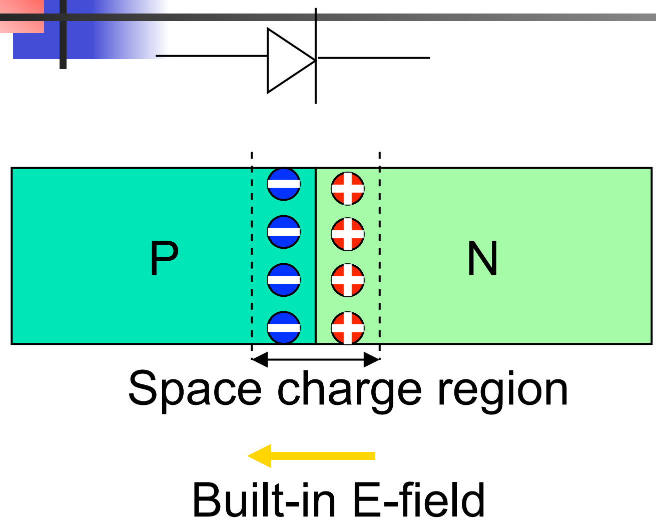
$$I_0 \propto \text{minority carrier density} \propto n_{p0}, p_{n0}$$

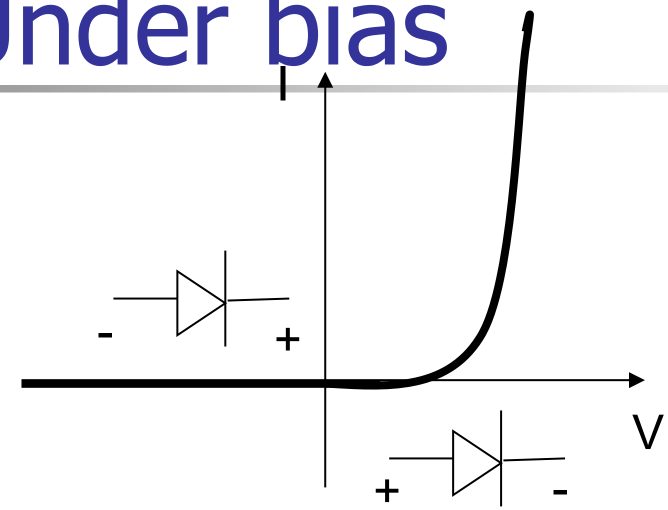
$$n_i^2 \propto \exp(-E_g / kT)$$

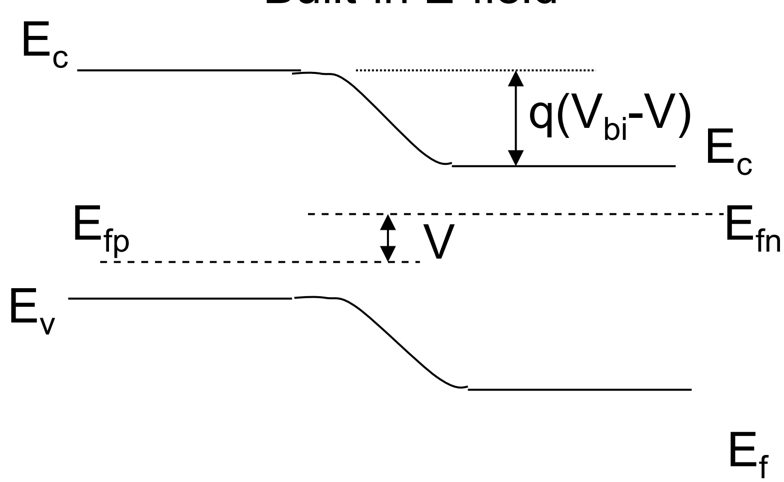
Forward current:

At equilibrium the net current is 0, so the forward current must be I_0

P-N Junction Under bias







Apply a bias of V:

Forward current:

The potential barriers for majority carriers is modified by an amount of qV compared to 0 bias, so the forward current is modified by a factor of $\exp(qV/kT)$: Boltzman distribution .

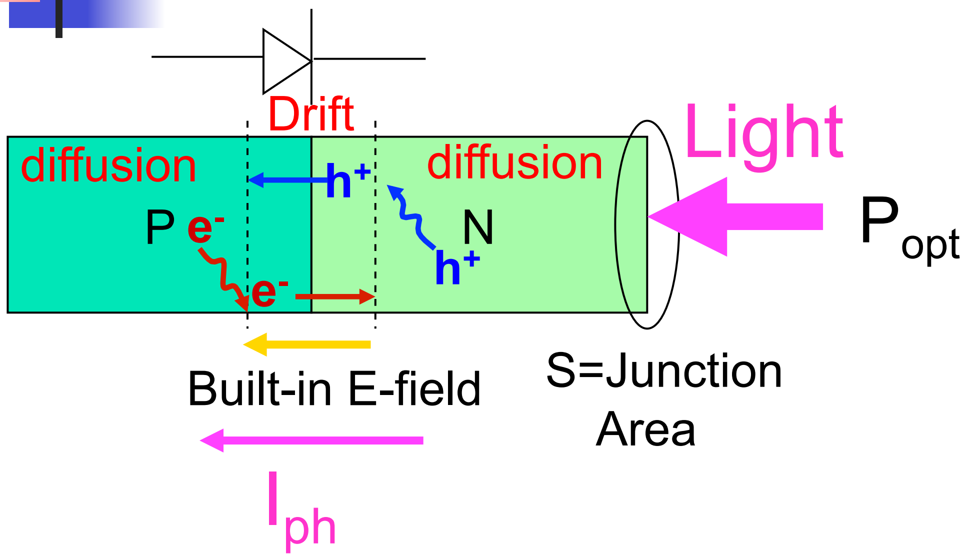
Therefore $I_{forward} = I_0 \exp(qV/kT)$

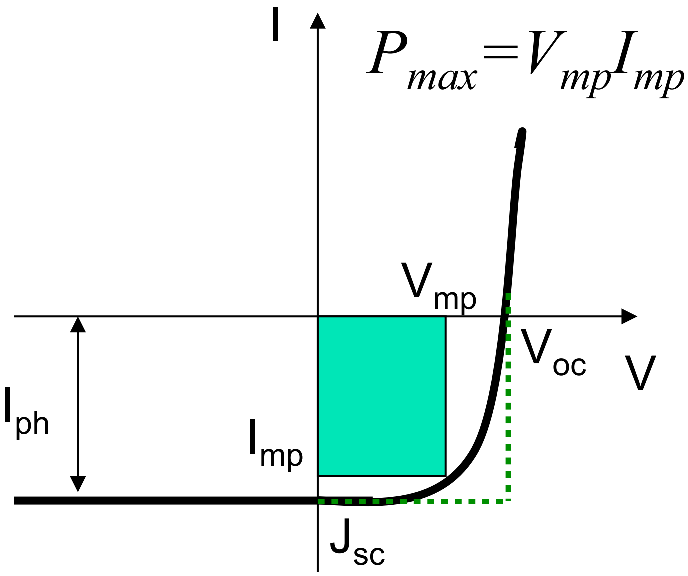
Reverse current

The same as 0 bias: $-I_0$

$$I = I_0\left[\exp(qV/kT) - 1\right]$$

Photocurrent: P-N Junction under Illumination





$$I = I_0\left[\exp(qV/kT) - 1\right] - I_{ph};$$

$$I_{sc} = I_{ph}; \qquad V_{oc} = (kT/q)\ln(1 + I_{ph}/I_0) \approx (kT/q)\ln(I_{ph}/I_0)$$

Fill Factor (FF) = $V_{mp}J_{mp}/V_{oc}J_{sc} \sim 0.6\text{-}0.8$

Energy conversion efficiency, η_{energy} = $FF^* V_{oc}{}^*J_{sc}/P_{opt}$

Solar Cells Devices

- Solar radiation spectrum is close to black-body radiation (broad spectrum)
- The photon energy needs to be absorbed by the semiconductor material.
  - Selection of band gaps is important for solar cells
- The pn junction potential drives current flow to create electrical power.

The Solar Cell

1) Principles of operation
2) Relevant performance metrics
3) Design for performance
4) Design for manufacturing
5) Design for application
6) What scale of production is consistent with (6)?