Announcements

- Exam #1 on Monday in class.
- No lecture on Friday. HW due under my office door by 12:30pm.
- Additional office hours on Thursday. Comment on GoPost as to preferred time(s).
- Example Exam to be posted. Solutions later.
- Review/problem session Sunday evening if there is interest.

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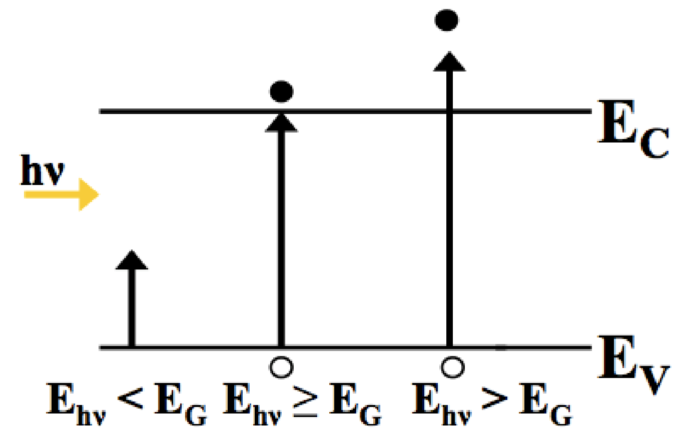
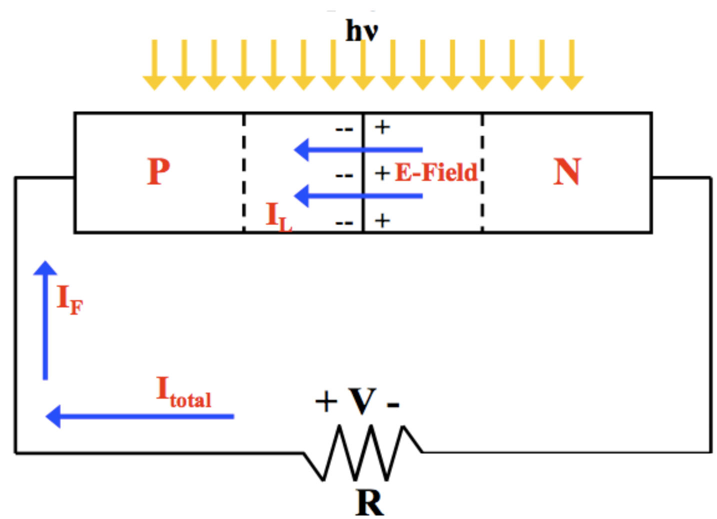
Photovoltaic Effect

- Incident light causes excitation of electrons from the valence band into the conduction band
  - $E_{hv} < E_G$: transparent
  - $E_{hv} \geq E_G$: photons are absorbed and electron-hole pairs (EHP) are photogenerated
  - $E_{hv} > E_G$: excess energy is lost as heat
- EHPs generated within a diffusion length of depletion region are swept across the junction by electric field creating photocurrent (I_L) in reverse bias direction. Other EHPs recombine before they can be collected.

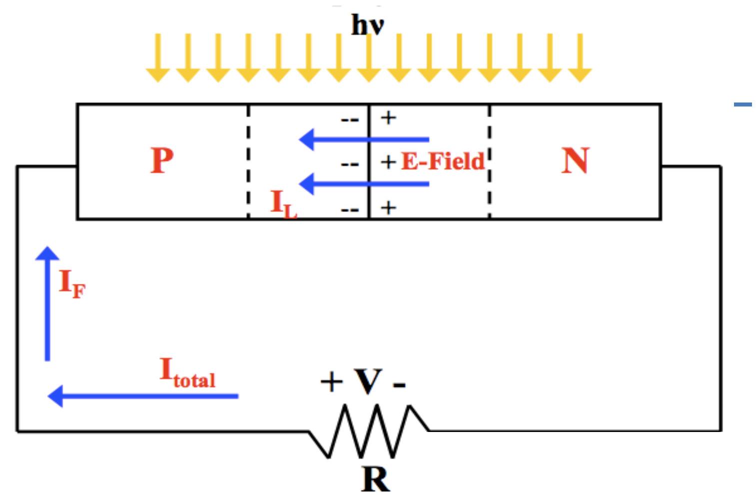


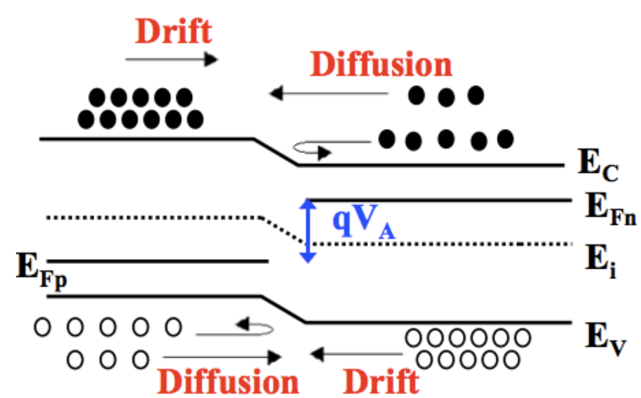


Photovoltaic Effect

- Basic solar cells are:
  - p-n junctions
  - Minority carrier devices
  - Voltage is not directly applied
  - $I_{total} = I_F - I_L = I_s\{\exp(qV/nkT)-1\} - I_L$
- The photo current produces a voltage drop across the resistive load, which forward biases the pn junction

1. Absorption of a photons ($E_{h\nu} \geq E_G$)
2. Formation of e-h pair (EHP)
3. EHP diffusion to Junction
4. Charge separation
5. Charge transport to anode (holes) and cathode (electrons)
6. Supply a direct current for the load





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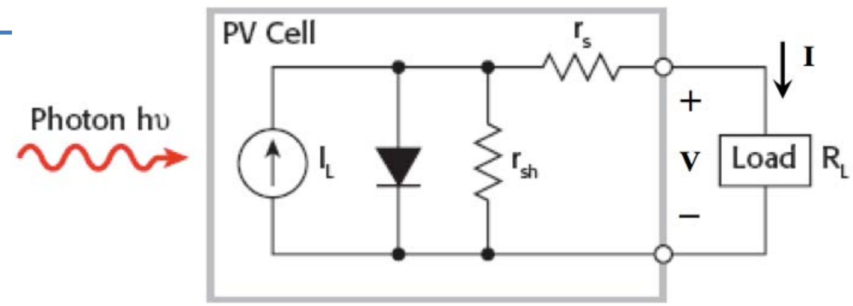
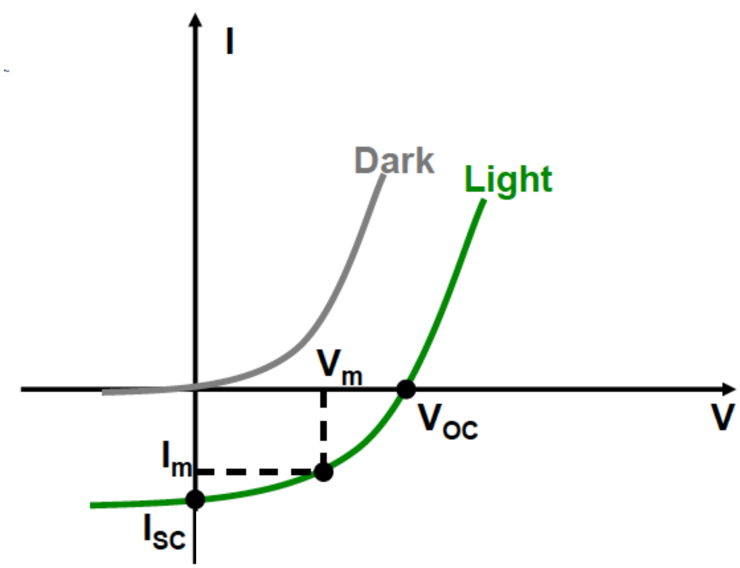
I-V Characteristics

- $I = I_L - I_s\{\exp(qV/nkT)-1\} - \{(V-Ir_s)/r_{sh}\}$
- $I_{SC} = I_L$: light induced current
- $V_{OC} = kT/q\{\ln(I_L/I_{OC})+1\}$



- V_m and I_m : Operating point yielding the max power output
- $FF = V_m I_m / V_{OC} I_{SC}$
- Power conversion efficiency:

$$\eta = P_{max} / P_{in} = V_m I_m / P_{in} = FF\ V_{OC} I_{SC} / P_{in}$$



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Solar Cell Operation

Key aim is to generate power by:

(1) Generating a large short circuit current, I_{sc}

(2) Generate a large open-circuit voltage, V_{oc}

(3) Minimise parasitic power loss mechanisms (particularly series and shunt resistance).

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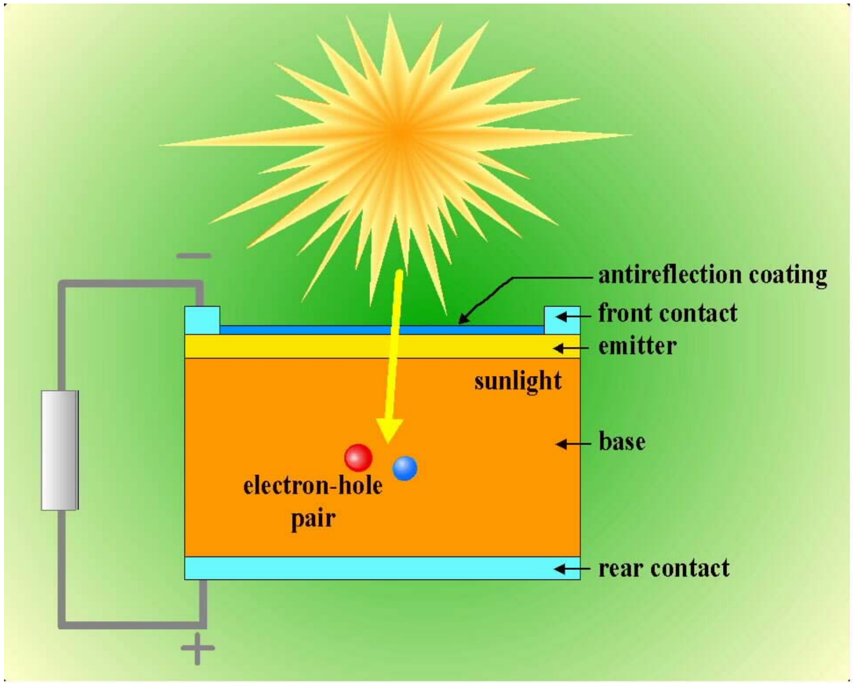
Short Circuit Current

J_{sc} depends on:

1. **Generation of light-generated carries**
   - **Minimize reflection**
   - **Absorb light in semiconductor and generate carriers**
   - **Reflection and absorption depend on characteristics of sunlight, solar cell optical properties, E_G, and solar cell thickness**

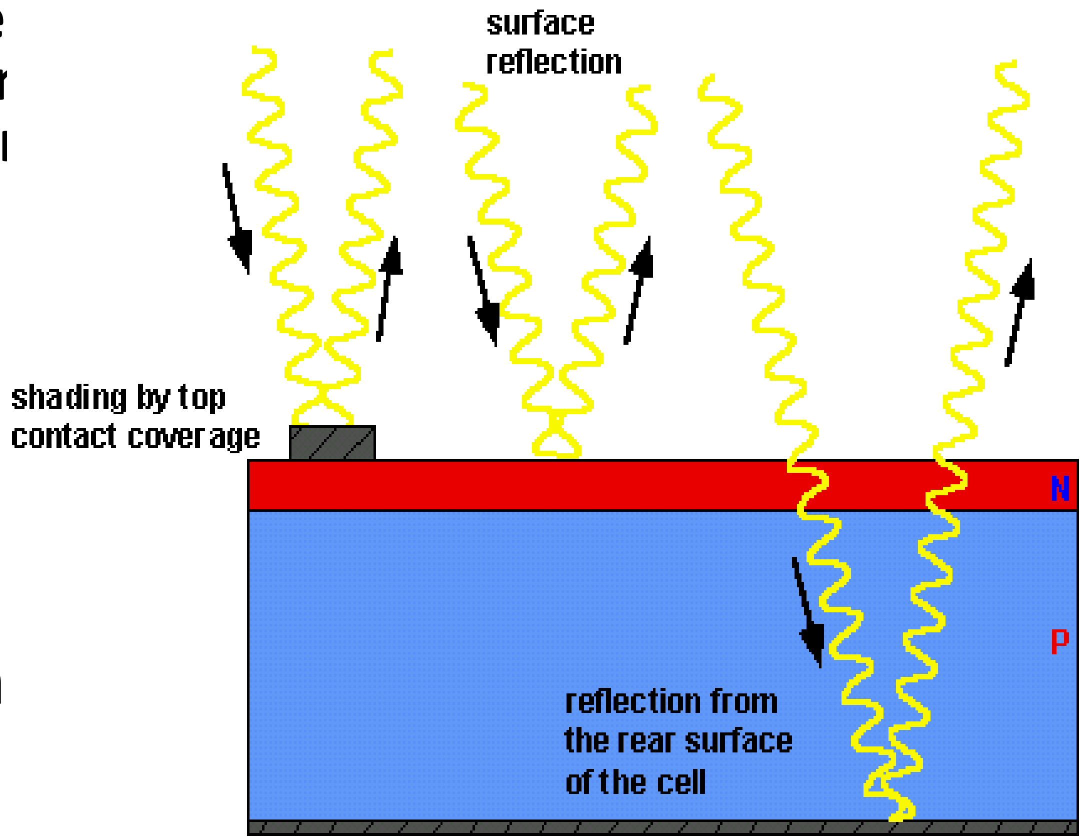
2. **Collection of light generated minority carriers**
   - **Depends on material and device parameters**



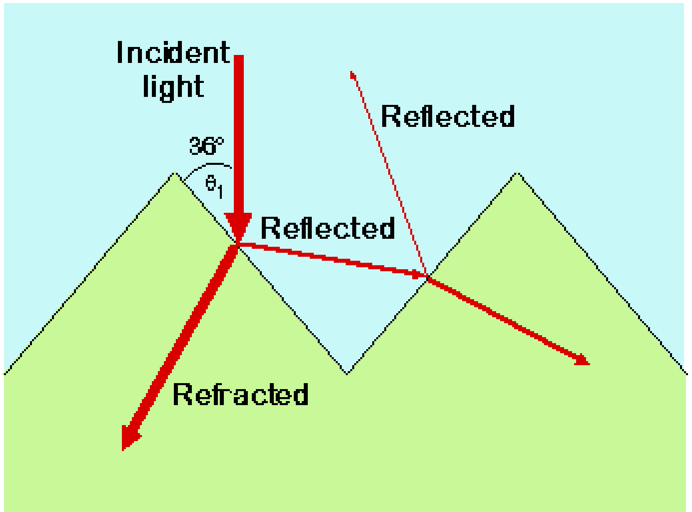
Optical Properties of Solar Cells

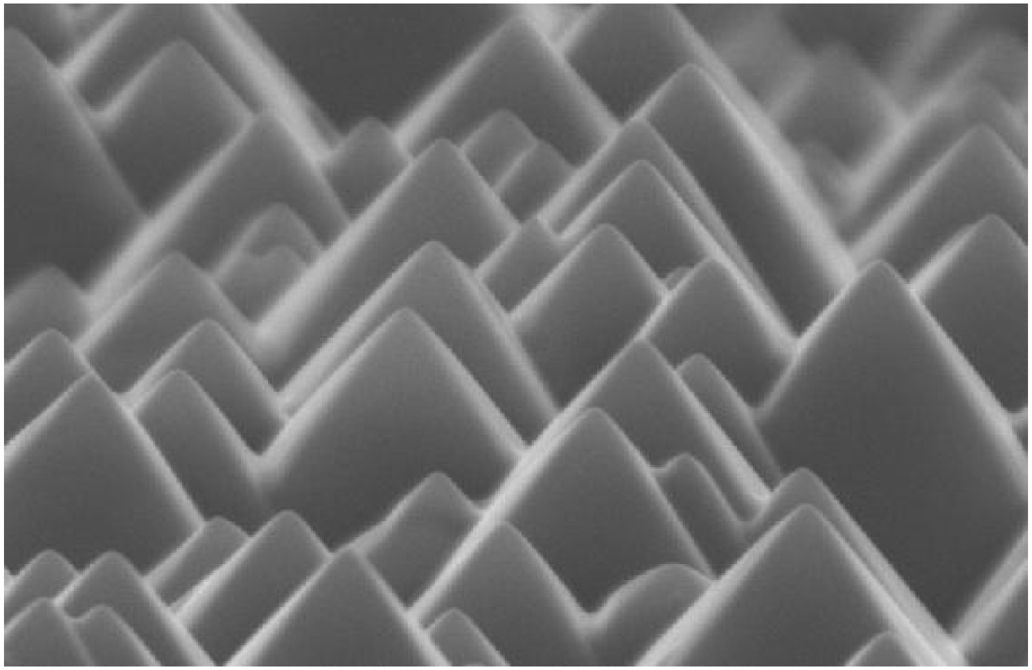
The optical properties (reflection, absorption) are key in achieving high currer To generate as many carrie as possible we need to:

- **Reduce reflection from silicon**
- **Reduce reflection from metal top surface.**
- **Increase absorption of light in semiconductor**



Reducing Reflection 2: Texturing

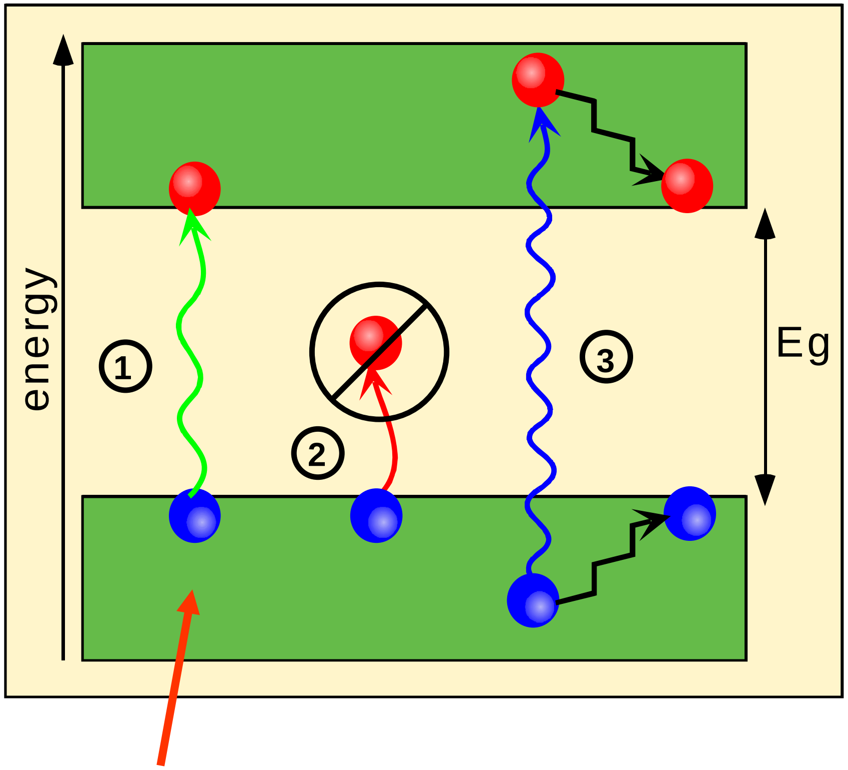




Absorption of photons: Eg

A photon in a solar cell can generate an electron-hole pair if it has an energy greater than the band gap

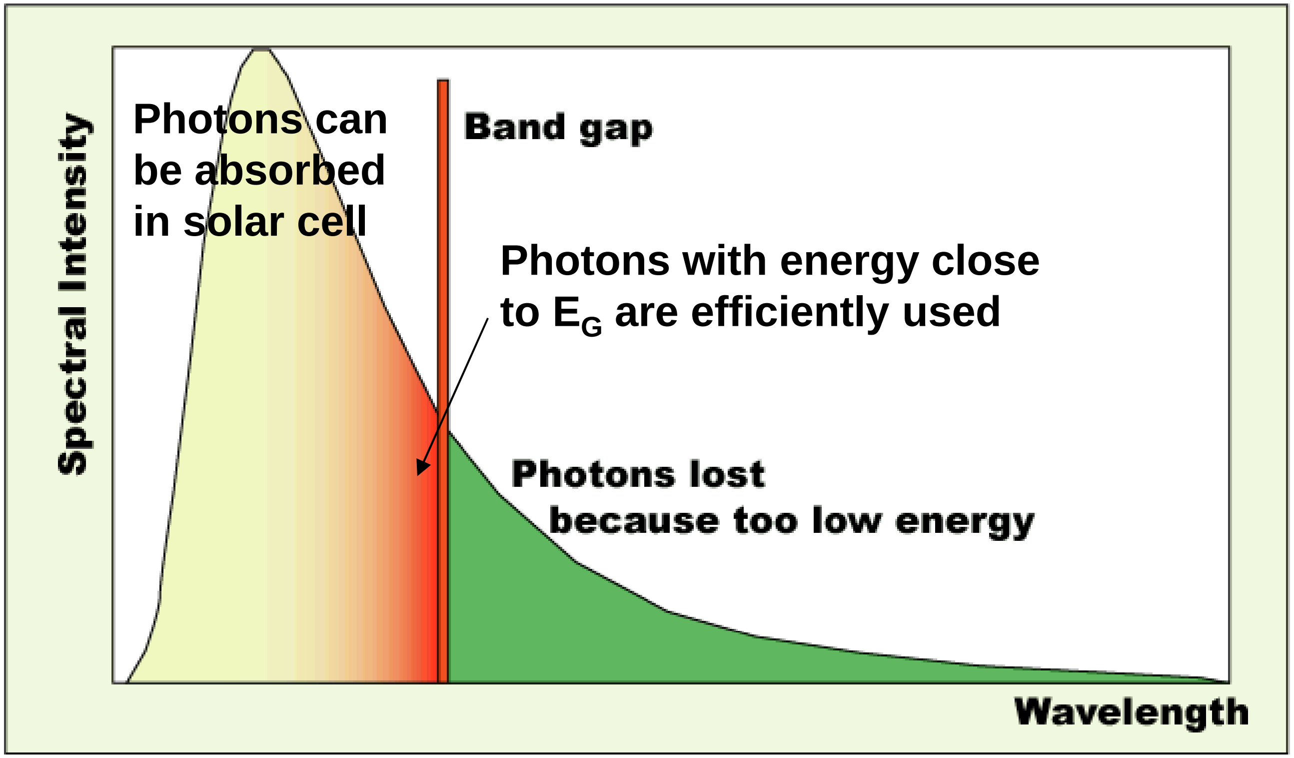
- **Photons with $E_{ph} < E_G$ are not absorbed and are lost**
- **If a photons has energy above E_G, the excess energy above E_G is lost as heat.**



Absorption process

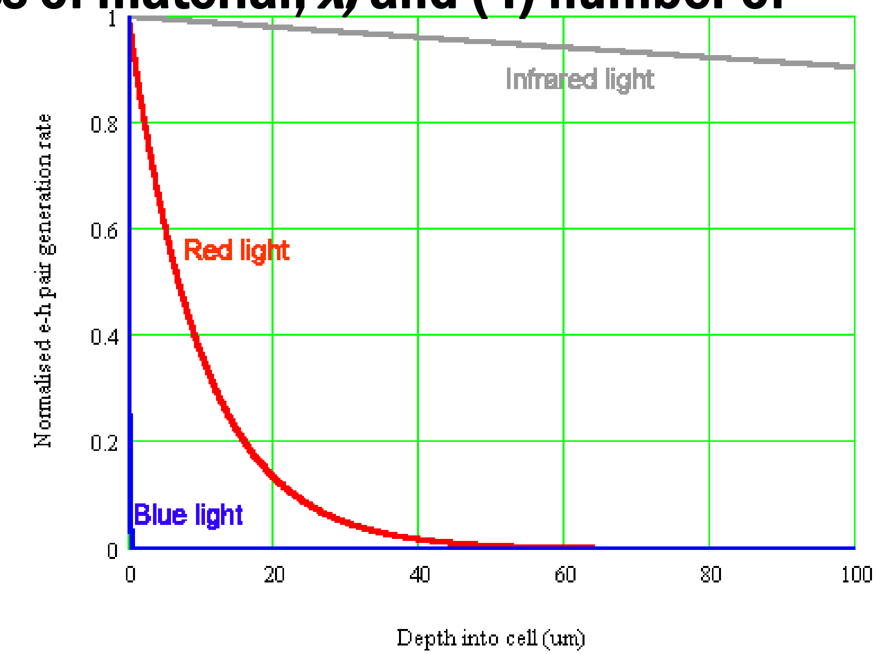
Absorption of photons: Eg

Value of band gap determines maximum possible current



Generation of carriers

Generation, G, depends on (1) absorption coefficient of material α, (2) incident wavelength, λ, (3) thickness of material, x, and (4) number of photons.



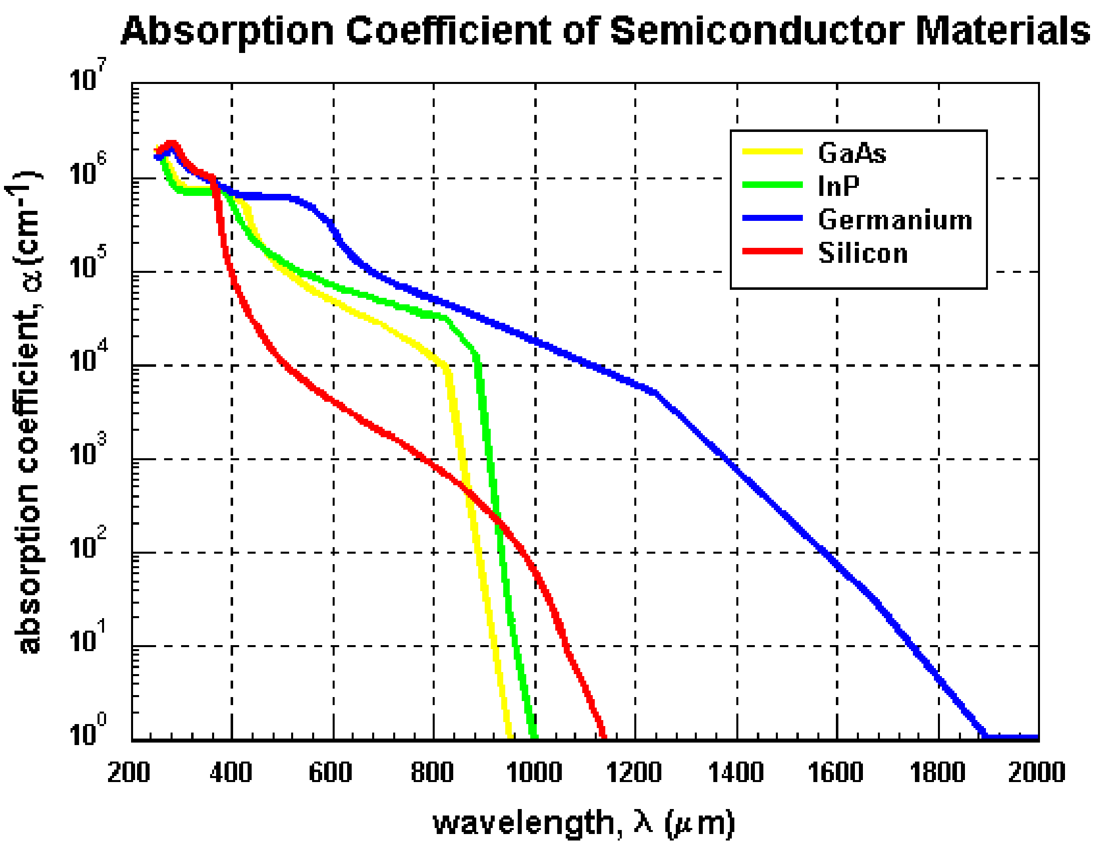
$$N_{ph} = N_s e^{-\alpha x}$$

Where N_{ph} **is the number of photons**
N_s **is photons at the surface**
α **is the absorption coefficient**
x is distance in the material

$$G = -\frac{dN_{ph}}{dx} = \alpha N_s e^{-\alpha x}$$

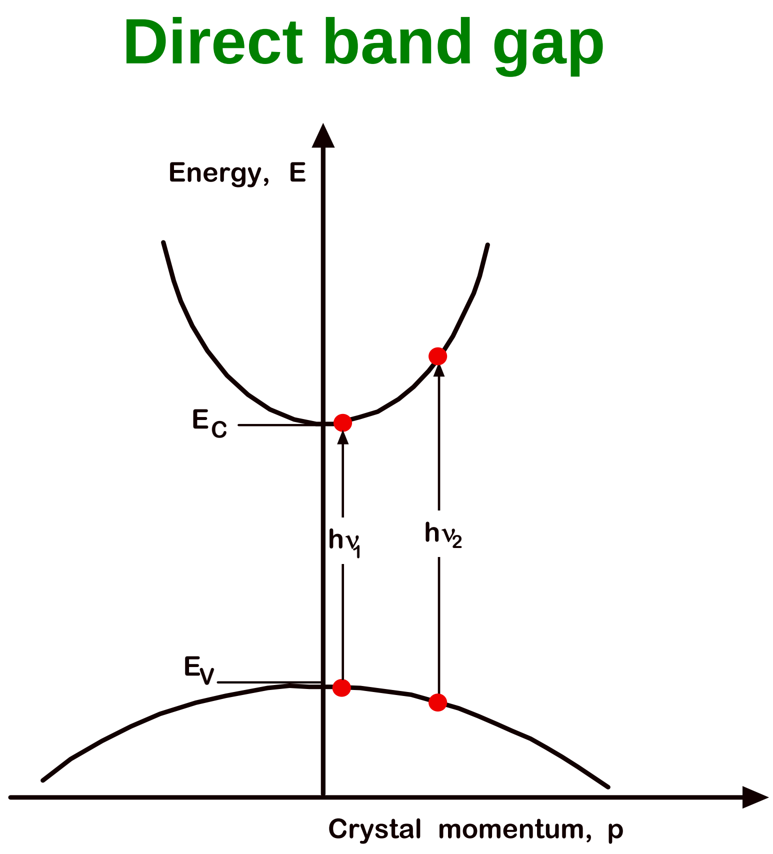
Absorption coefficient, α

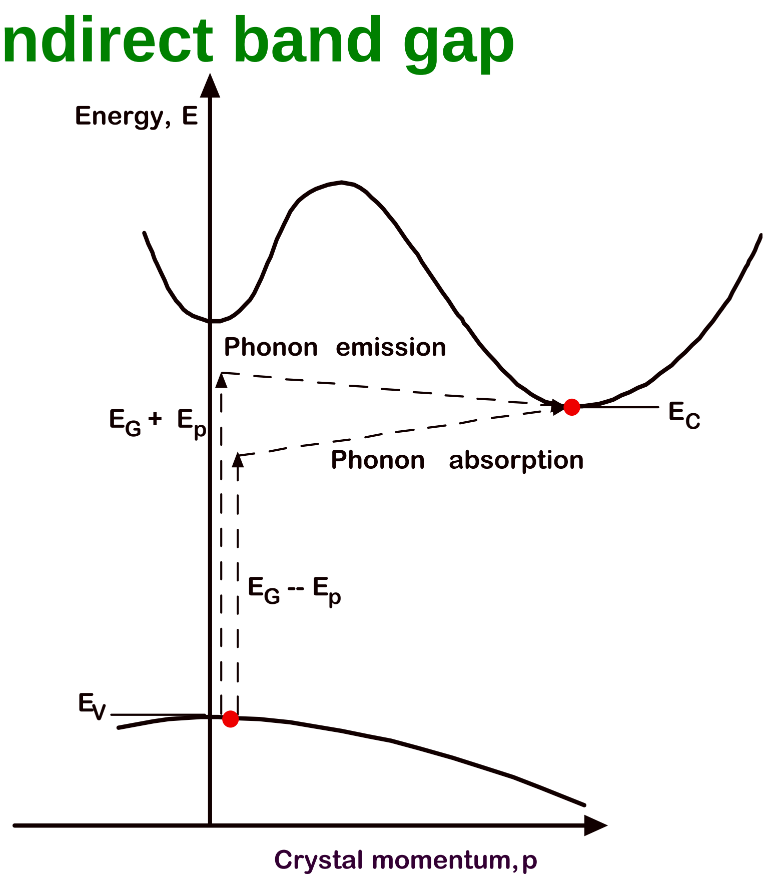
- α of a material determines generation as a function of wavelength
- α small for photons with energy below E_G – no absorption below band gap.
- For photon energies above E_G, α will determine the thickness



Absorption coefficient

Absorption coefficient strongly affected determined by type of band gap.

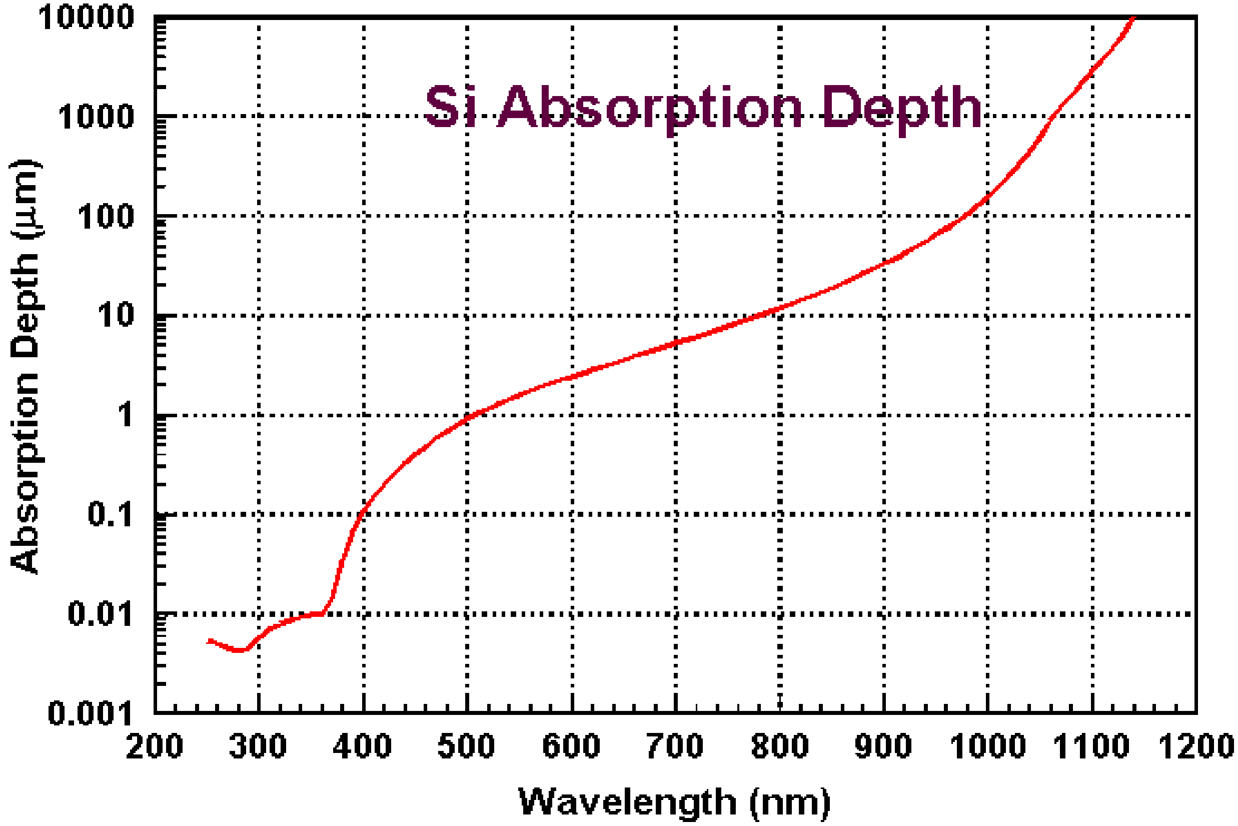




Thickness of material

The thickness of the material determines how much light is absorbed.

Absorption depth is thickness requires to absorb ~60% (1 – 1/e) of incident light

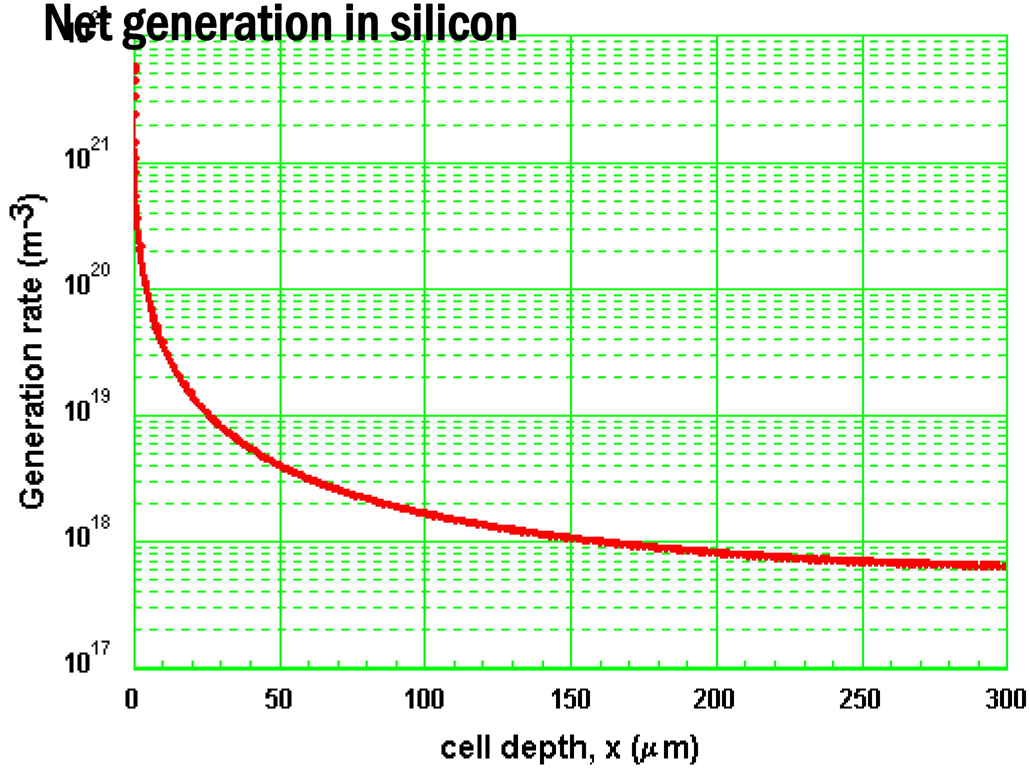


Net Generation Rate

Net generation rate is the integration over all wavelengths.

- High at surface
- In silicon, significant absorption even after 200 μm.

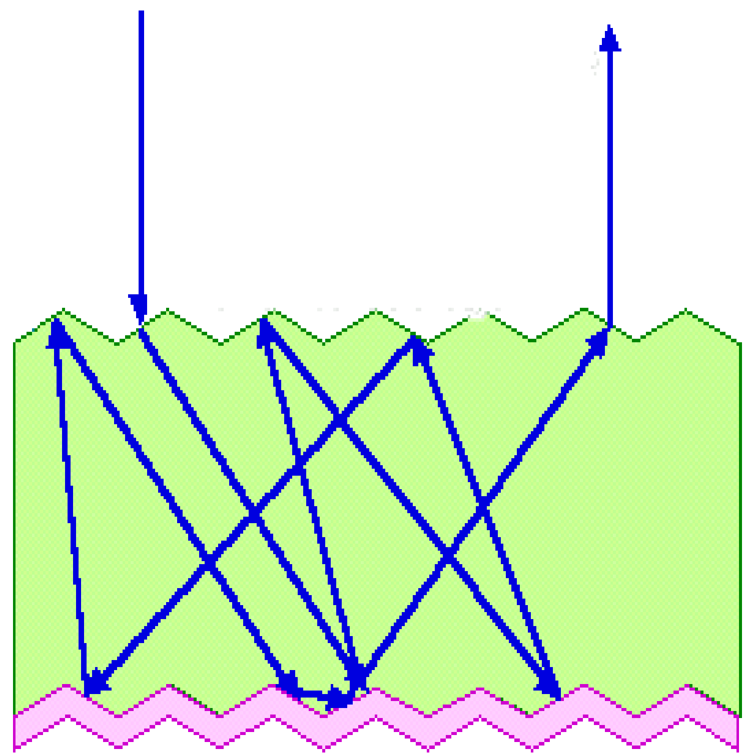
Net generation in silicon



Increasing Absorption

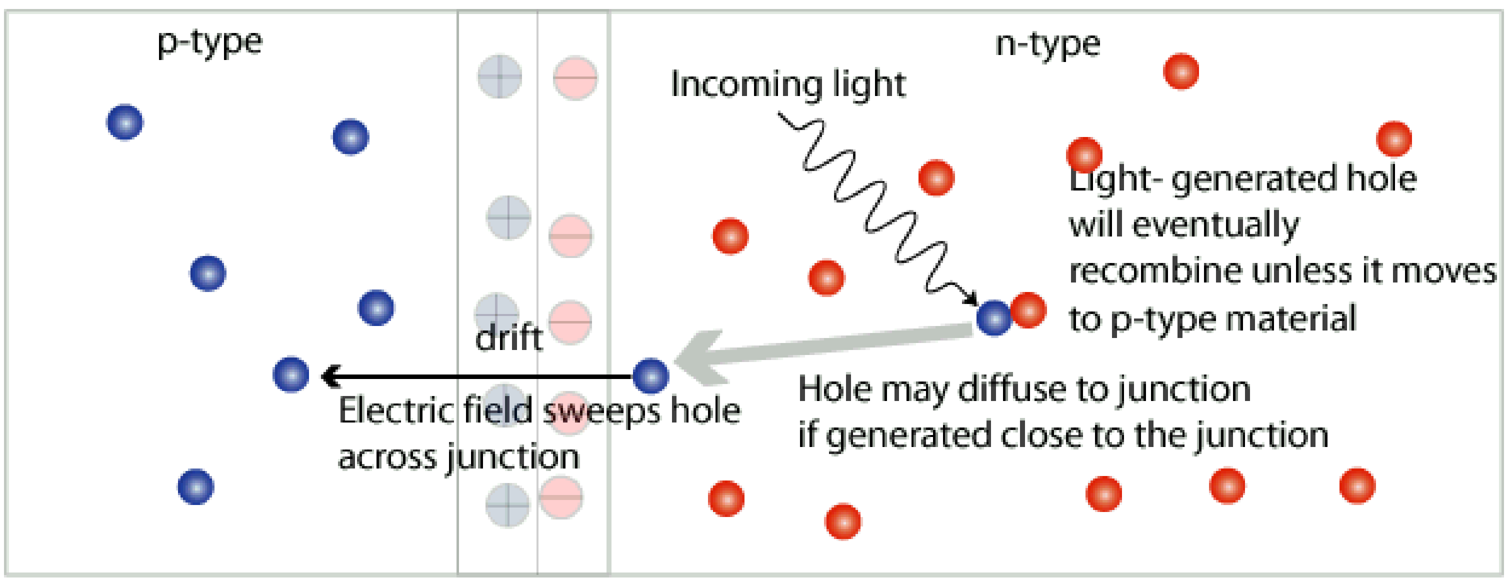
Light trapping increases the "optical thickness" of a material

- **Physical thickness can remain low**
- **Allows carriers to be absorbed close to the junction**



Collection probability

- **A light generated minority carrier can readily recombine.**
- **If it the carrier reaches the edge of the depletion region, it is swept across the junction and becomes a majority carrier. This process is collection of the light generated carriers.**
- **Once a carrier is collected, it is very unlikely to recombine.**

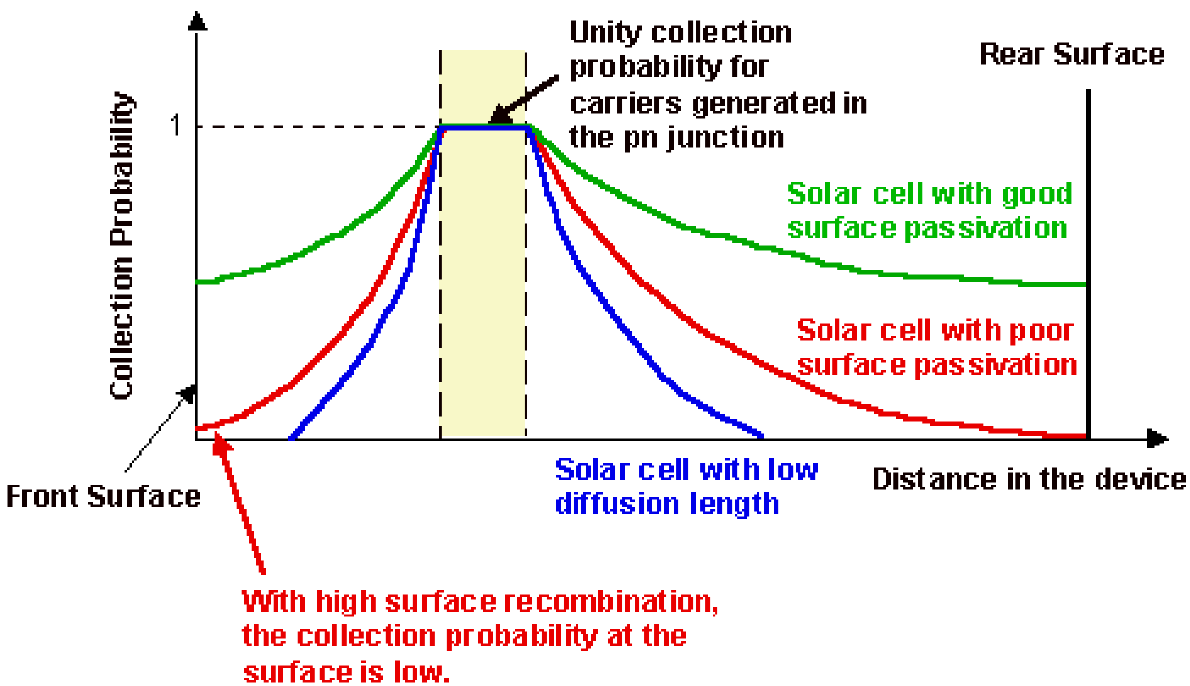


Recombination Revisited

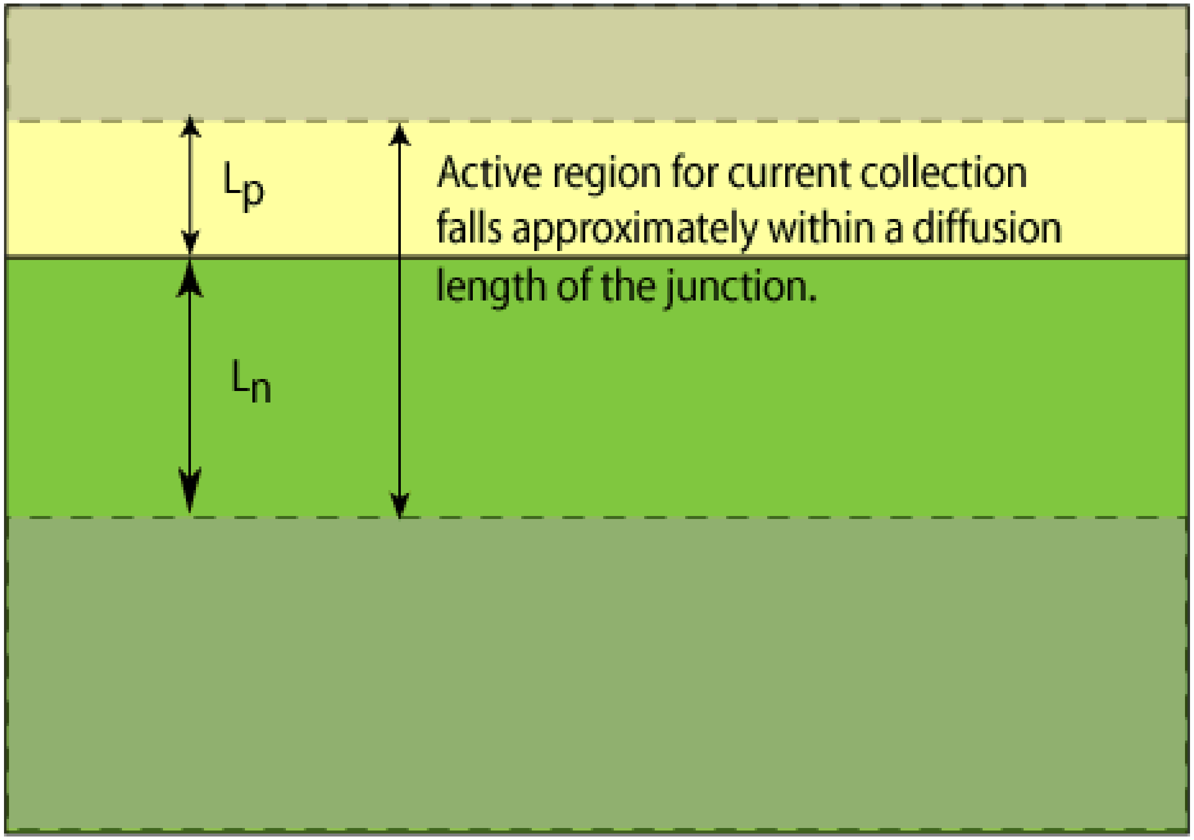
- In solar cells, two addition recombination mechanisms exist which have a large impact on the devices: Surface recombination and defect (grain boundary) recombination: Both are “surface” or localized phenomena rather than bulk phenomena.
- The physical cause of these recombination mechanisms is the interruption of the crystal lattice.
- Surface and/or interface recombination affects the entire region associated with that surface since there is a diffusion current towards the recombination site.

Collection probability

- **Collection probability is the probability that a light generated carrier will reach the depletion region and be collected.**
- **Depends on where it is generated compared to junction and other recombination mechanisms, and the diffusion length.**



Collection probability



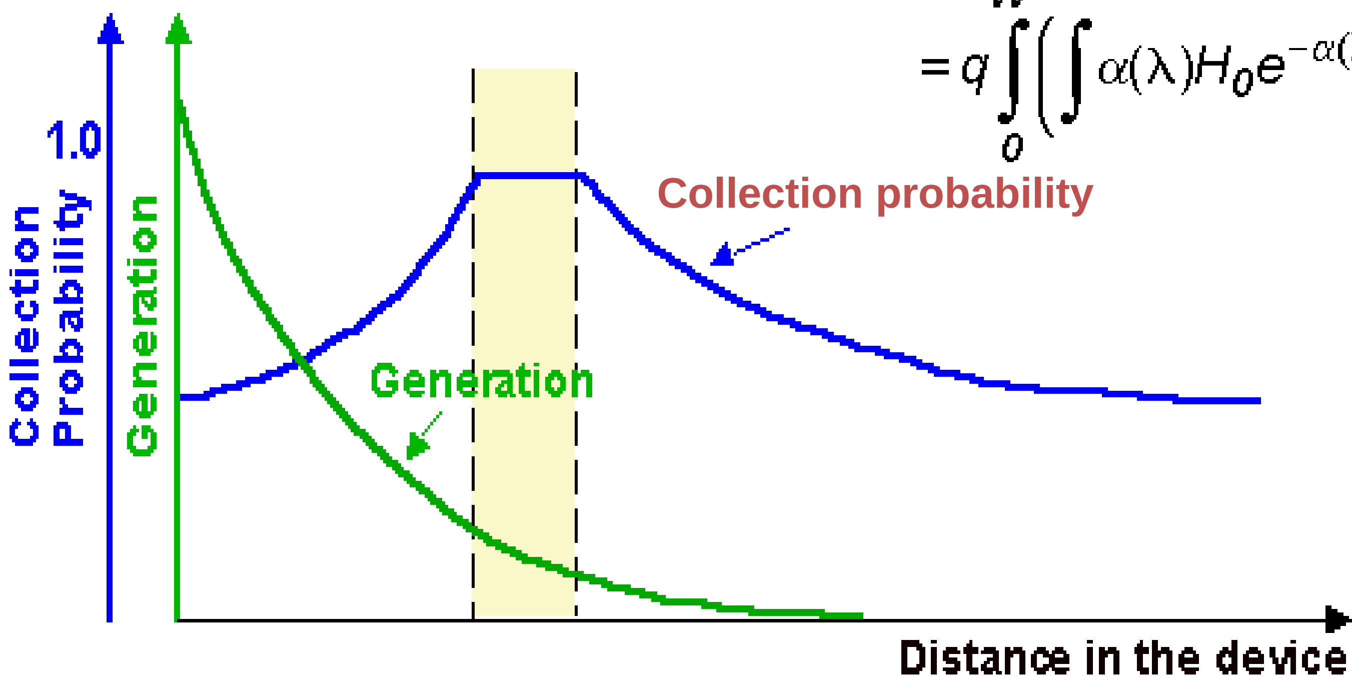
Collection probability is low further than a diffusion length away from junction

Short Circuit Current

J_{sc} determined by generation rate and collection probability

$$J_L = q\int_0^W G(x)CP(x)dx$$

$$= q\int_0^W \left(\int \alpha(\lambda)H_0 e^{-\alpha(\lambda)x} d\lambda\right) CP(x)dx$$



Collection Summary

- A carrier has a high probability of being collected if it is generated closer to the junction than to a recombination site and if it generated within a diffusion length of the junction
  - Difficult to achieve high collection near front surface (and also rear, but fewer carriers generated there).
  - Emitter junction is usually fairly thin.
- Minority carrier diffusion length (and surface recombination) are key parameters for high collection.

Short Circuit Current

- **Can calculate I_{sc} using the identical approach as was used to calculate the diode equation, but setting G ≠0.**
- **Following this approach, the differential equation to be solved is:**

$$\frac{d^2 n(x)}{dx^2} = \frac{\Delta n}{\tau_n D_n} - \frac{G(x)}{D_n}$$

- **The solution to this differential equation is simple only when G = constant. In this case, the carrier concentration is:**

$$\Delta n(x) = Ae^{-x/L_n} + Be^{x/L_n} + G\tau_n$$

Short Circuit Current

- **Applying the same boundary conditions as in the ideal diode case, differentiating to find the current, and equating the currents on the n-type and p-type sides, we get:**

$$J = \left[q\frac{D_n}{L_n} n_{p0} + q\frac{D_p}{W_n} p_{n0} \right] \left[e^{qV/kT} - 1 \right] - qG\left(L_n + W_p / 2 + W \right)$$

which is usually written as:

$$J = J_0 \left[e^{qV/kT} - 1 \right] - J_L$$

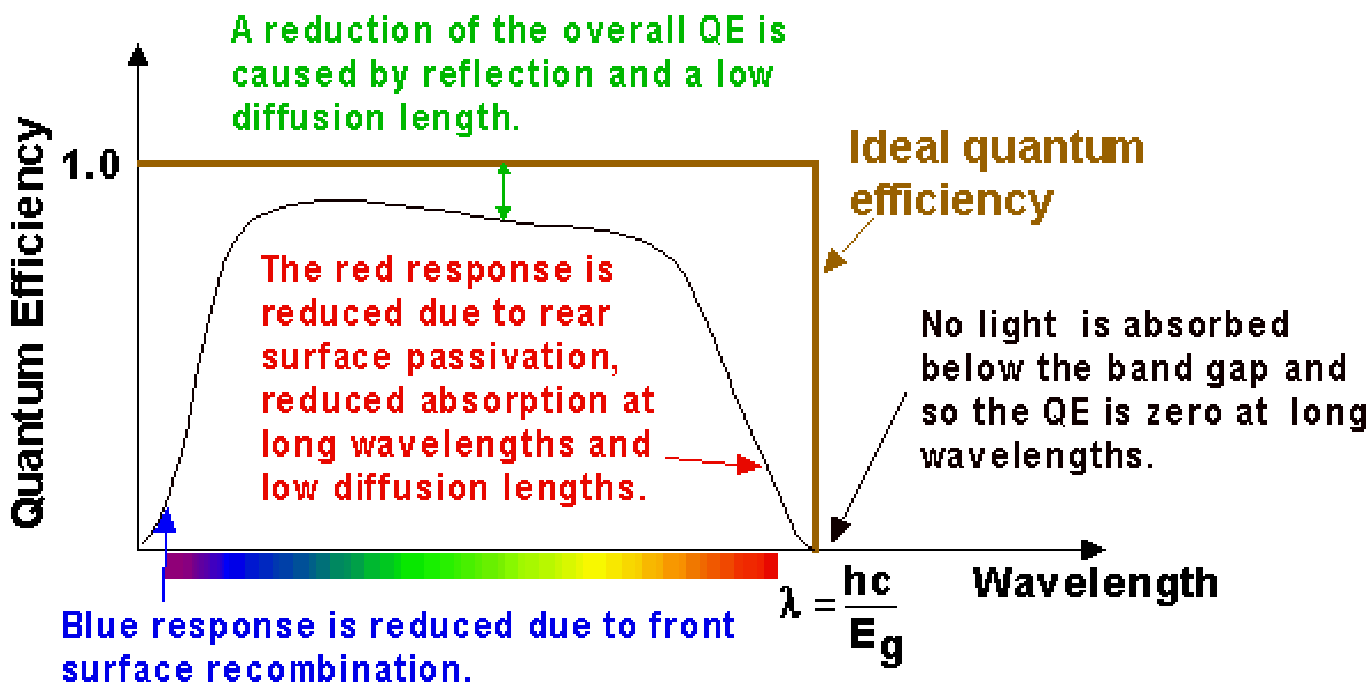
where:

$$J_L = qG\left(L_n + W_n / 2 + W \right) \quad J_0 = q\left[\frac{D_n n_i^2}{L_n N_A} + \frac{D_p n_i^2}{W_n N_D} \right]$$

(same as a diode)

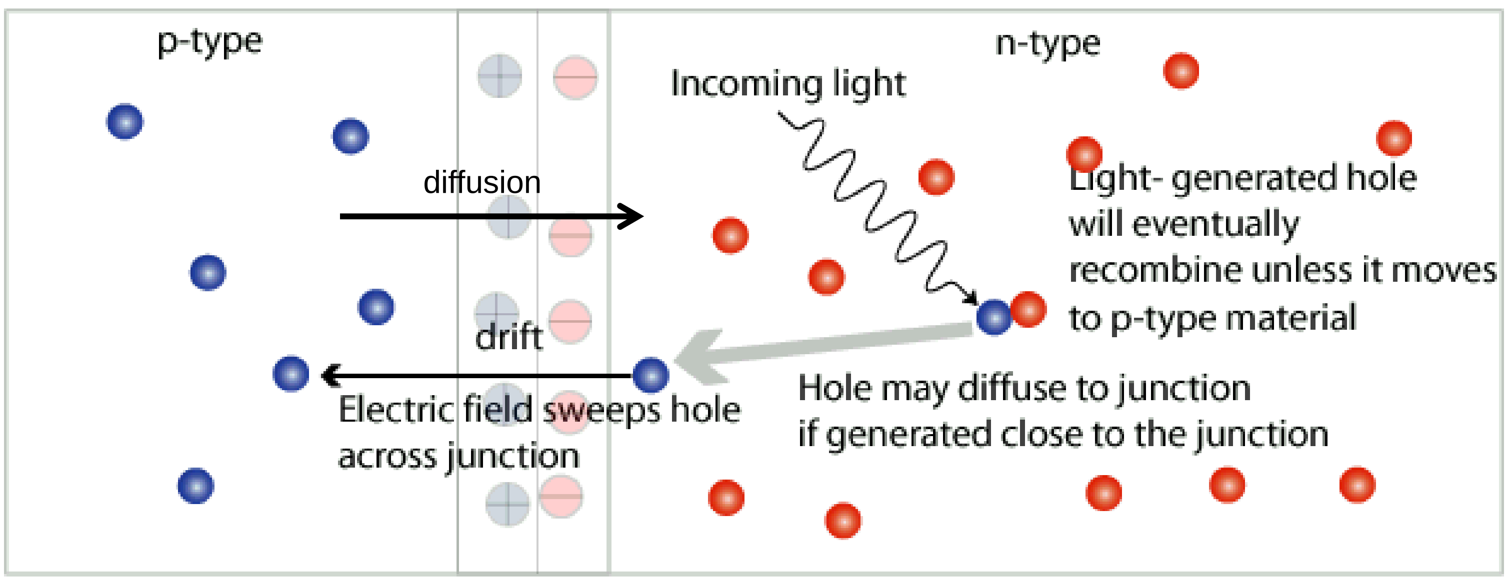
Quantum Efficiency

Collection probability difficult to measure, so instead use quantum efficiency, defined as ratio of photons incident to carriers collected.



Open Circuit Voltage

- **If collected light-generated carriers are not extracted from the solar cell but instead remain, then a charge separation exists.**
- **The charge separation reduces the electric field in the depletion region, reduces the barrier to diffusion current, and causes a diffusion current to flow.**



High Open Circuit Voltage

- **For a given band gap, a high open circuit voltage arises from low recombination in the active regions within a diffusion length of the junction**

$$J = J_0(\exp(qV/nkT) - 1) - J_{sc}$$

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_0} + 1\right)$$

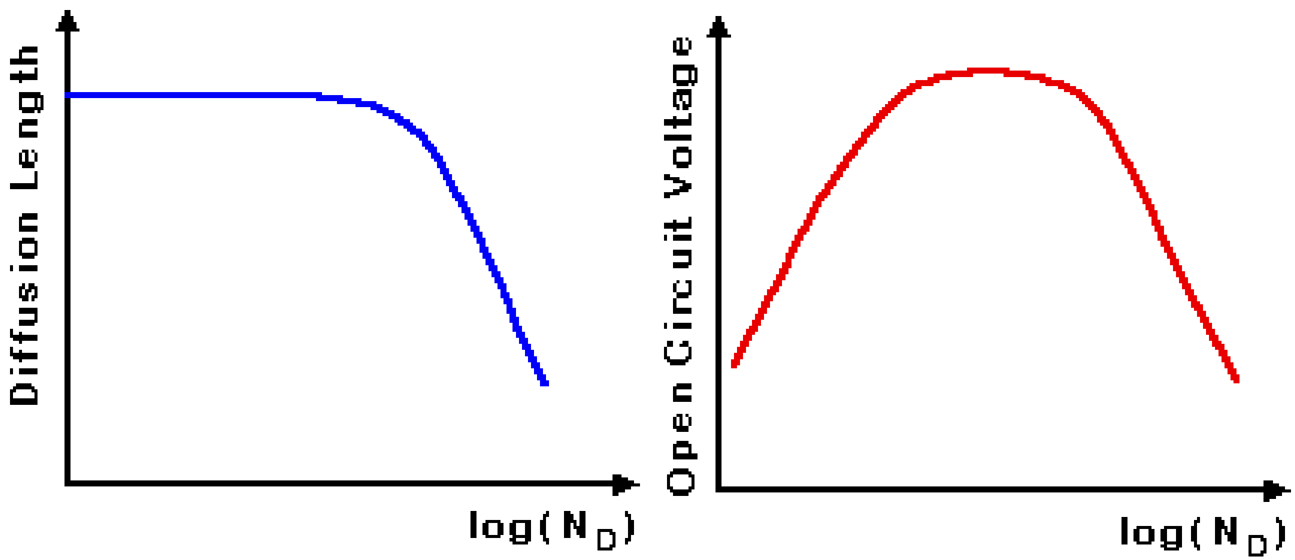
Note: J is current density A/cm^2, I is current.

Voc and doping

For a fixed E_G, trade-off between doping and diffusion length

$$V_{OC} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_0}+1\right)$$

$$I_0 = qA\left(\frac{D_n n_i^2}{L_n N_A}+\frac{D_p n_i^2}{L_p N_D}\right)$$



Maximizing efficiency

$$\eta = \frac{I_{sc}\, V_{oc}\, FF}{P_{in}}$$

↑ I_{sc}

- ↓ E_G
- ↓ Reflection
  - Surface
  - Metal
- ↑ L_n, L_p
- ↓ S_r
- x_j optimum

↑ V_{oc}

- ↑ E_G
- ↑ doping
- ↑ L_n, L_p
- ↓ S_r

Doping and diffusion length are related

↑ FF

- ↓ Series R
  - Metal
  - Emitter
    - ↑ doping
    - Thick emitter