Primer on Semiconductors

Unit 4: Carrier Transport, Recombination, and Generation

Lecture 4.5: Carrier generation

Mark Lundstrom

lundstro@purdue.edu
Electrical and Computer Engineering
Purdue University
West Lafayette, Indiana USA

PURDUE UNIVERSITY

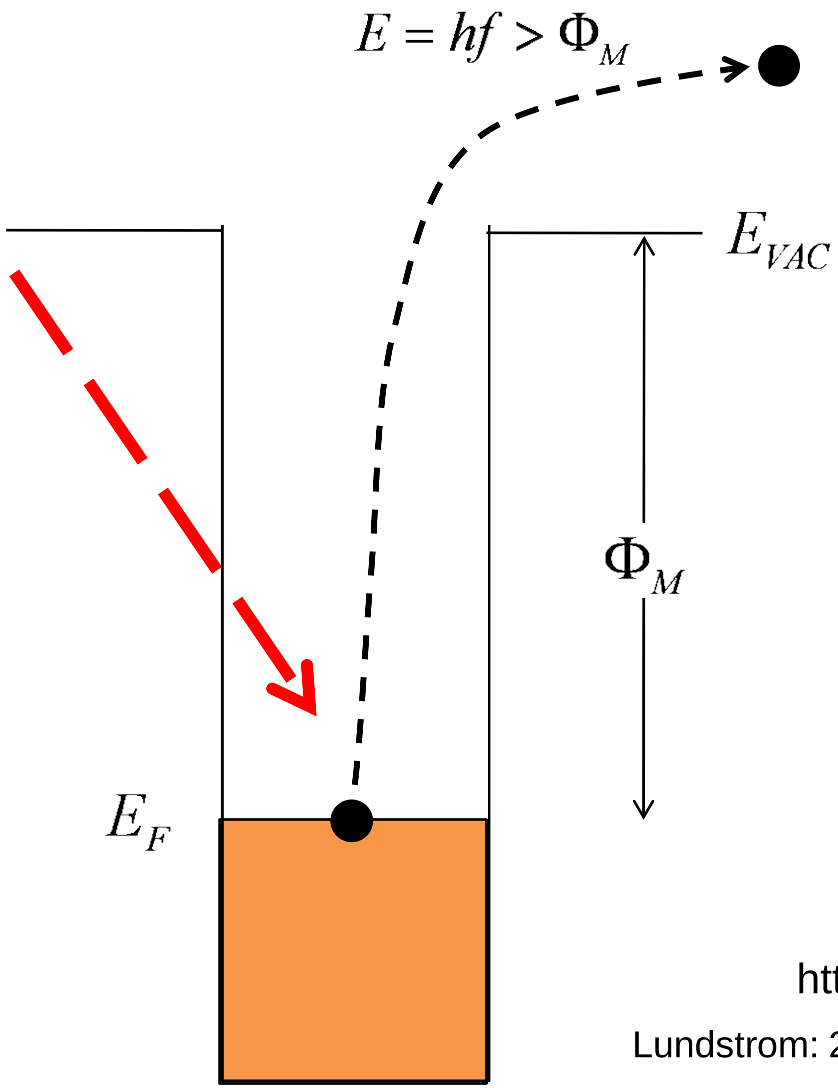
Recombination

$$\boxed{\Delta n(t) = \Delta n(t=0)\, e^{-t/\tau_n}}$$

(low level injection)

The minority carrier lifetime is controlled by radiative, Auger, or defect-assisted process – or by some combination of these.

Photoelectric effect (optical generation)



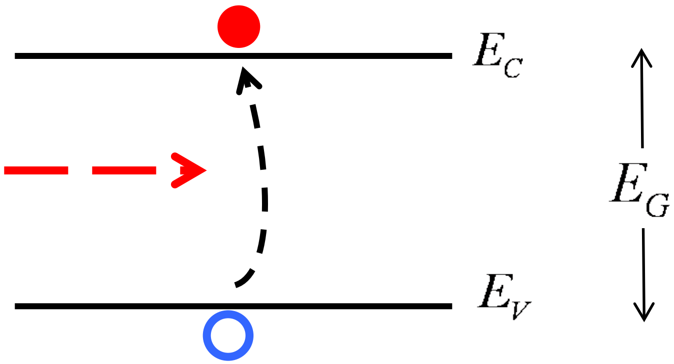
Einstein, in 1905, when he wrote the Annus Mirabilis papers

http://en.wikipedia.org/wiki/Photoelectric_effect

Optical generation in semiconductors

$$\lambda < \frac{hc}{E_G}$$

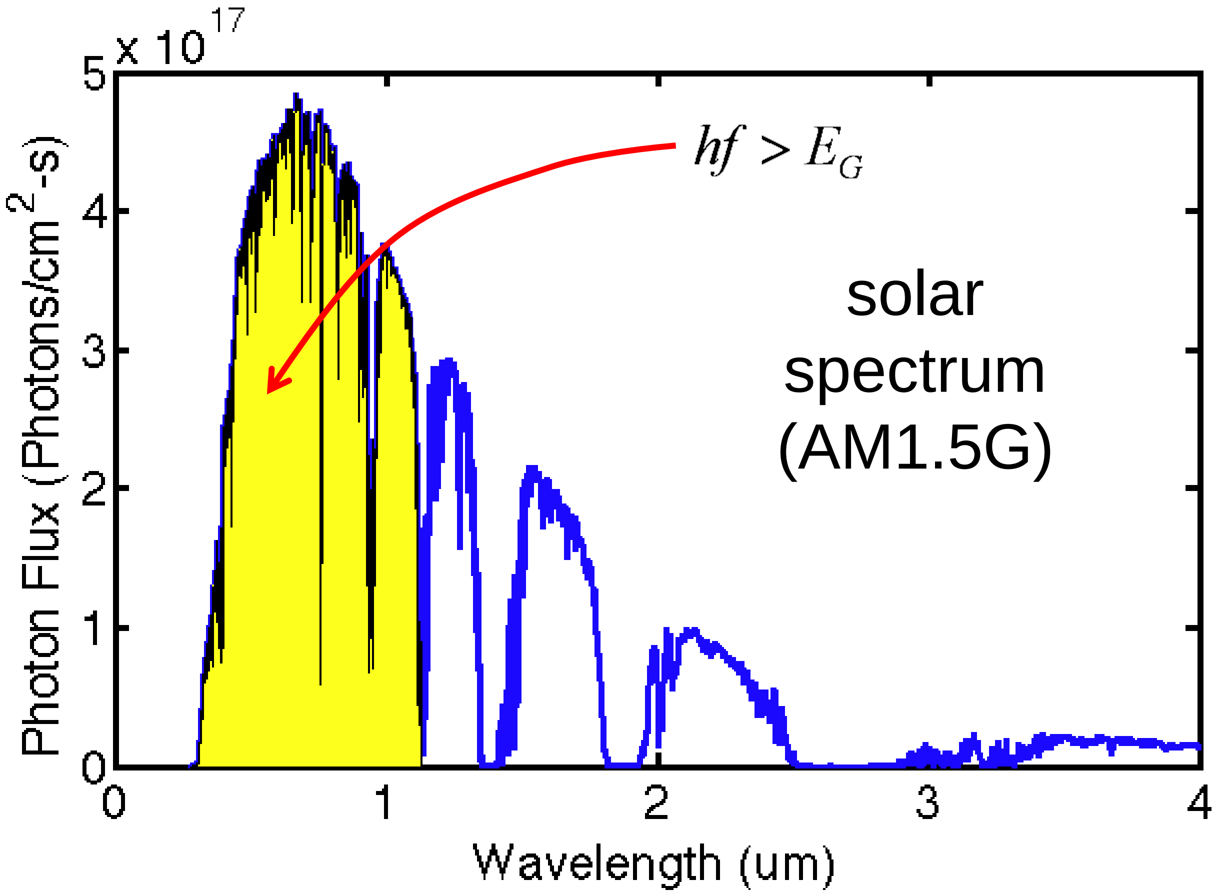
$$E = hf > E_G$$



$$f\lambda = c \qquad f = \frac{c}{\lambda} \qquad E = hf = \frac{hc}{\lambda}$$

Carrier generation from a solar spectrum

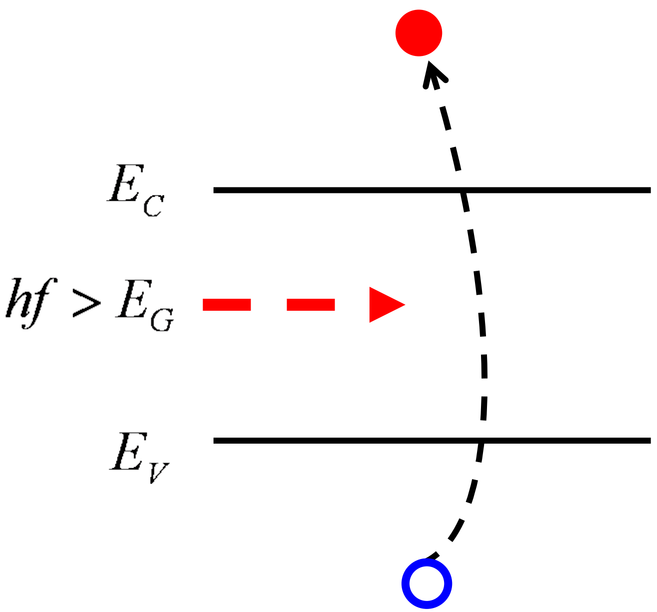
Example: Silicon E_G = 1.1 eV. Only photons with a wavelength smaller than 1.13 ⌠m will be absorbed.



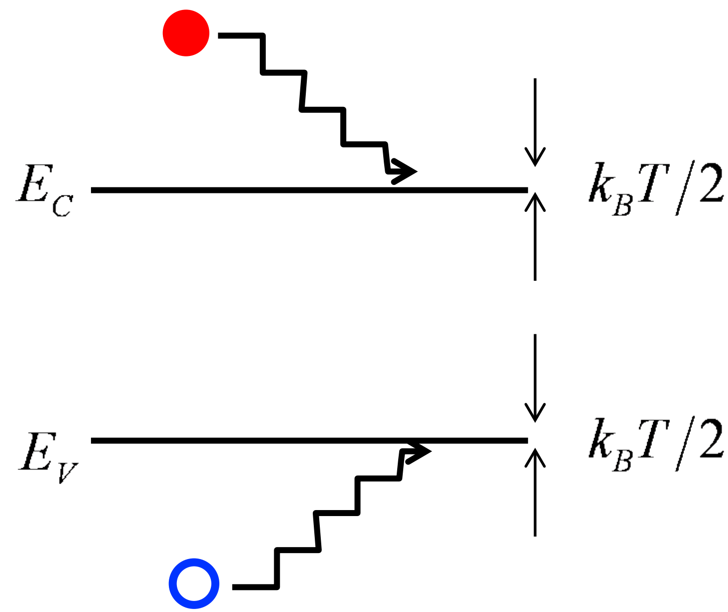
What happens to the extra energy?

Thermalization

Energy is lost for photons with energy greater than the bandgap.

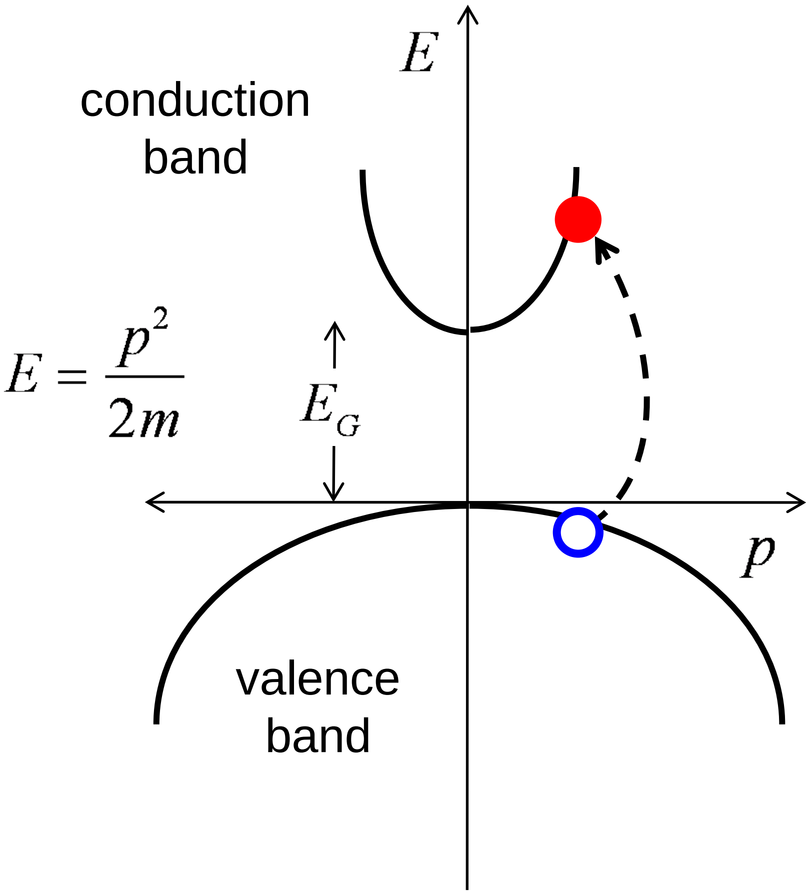


Carriers are created with excess energy.



Extra energy is lost due to thermalization as carrier relax back to the band edge.

Thermalization on an *E*(*k*) diagram

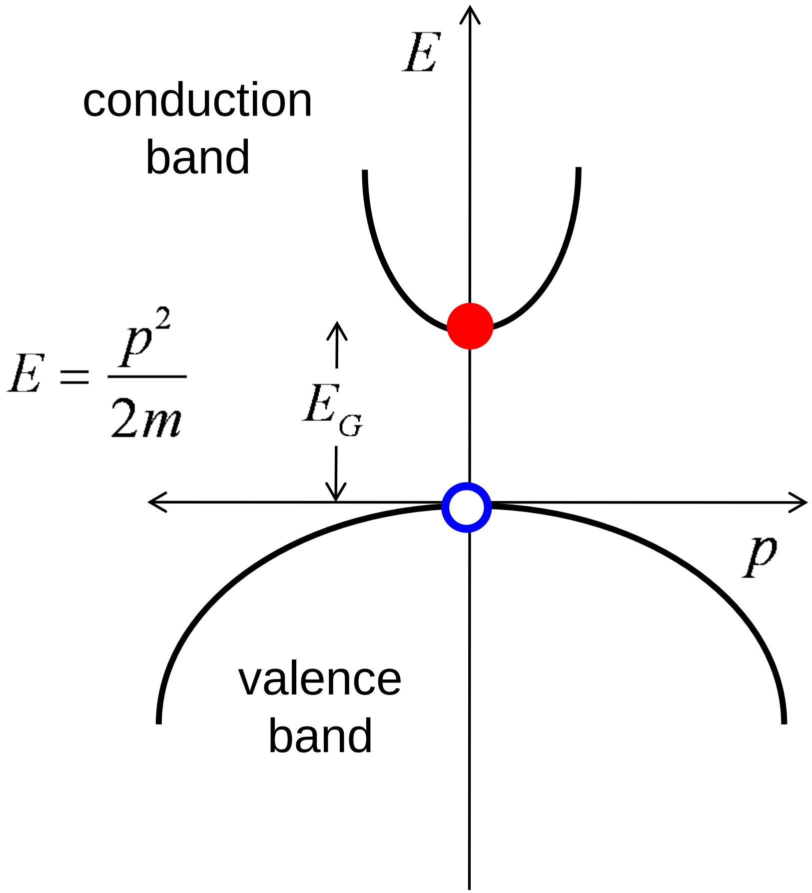


Electrons move downhill to lower their energy.

Holes move up to lower their energy.

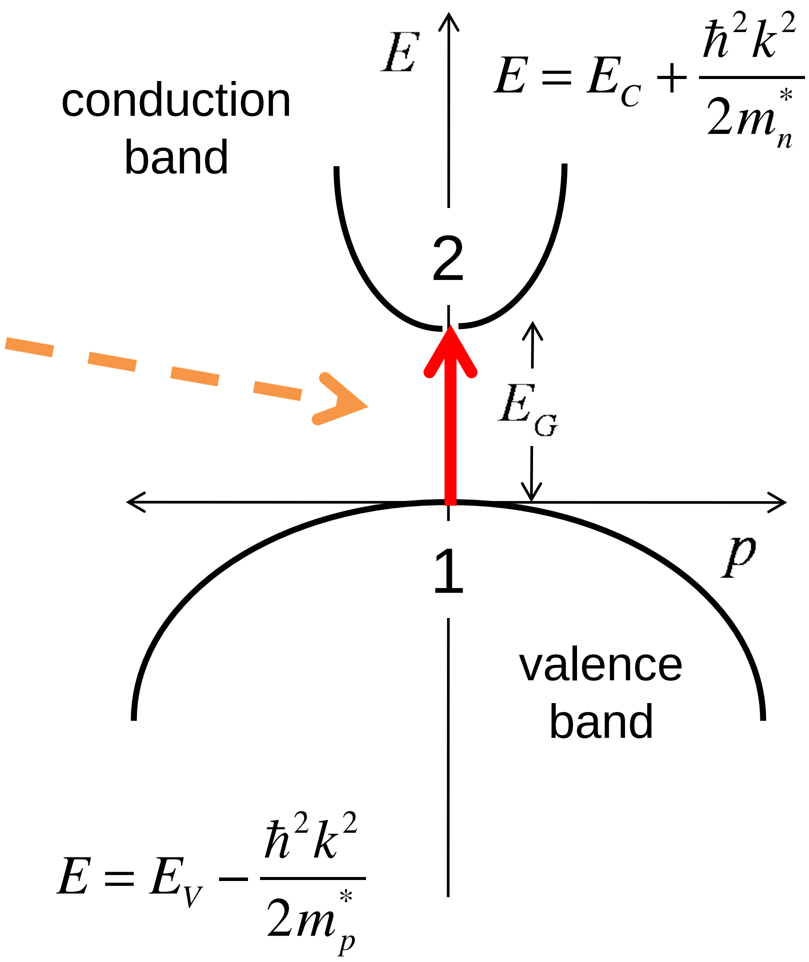
(This is an electron energy diagram)

Thermalization on an *E*(*k*) diagram



The excess energy is released as heat.

Optical absorption in a **direct gap** semiconductor



Conservation of energy:

$$E_{ph} = hf \approx E_G$$

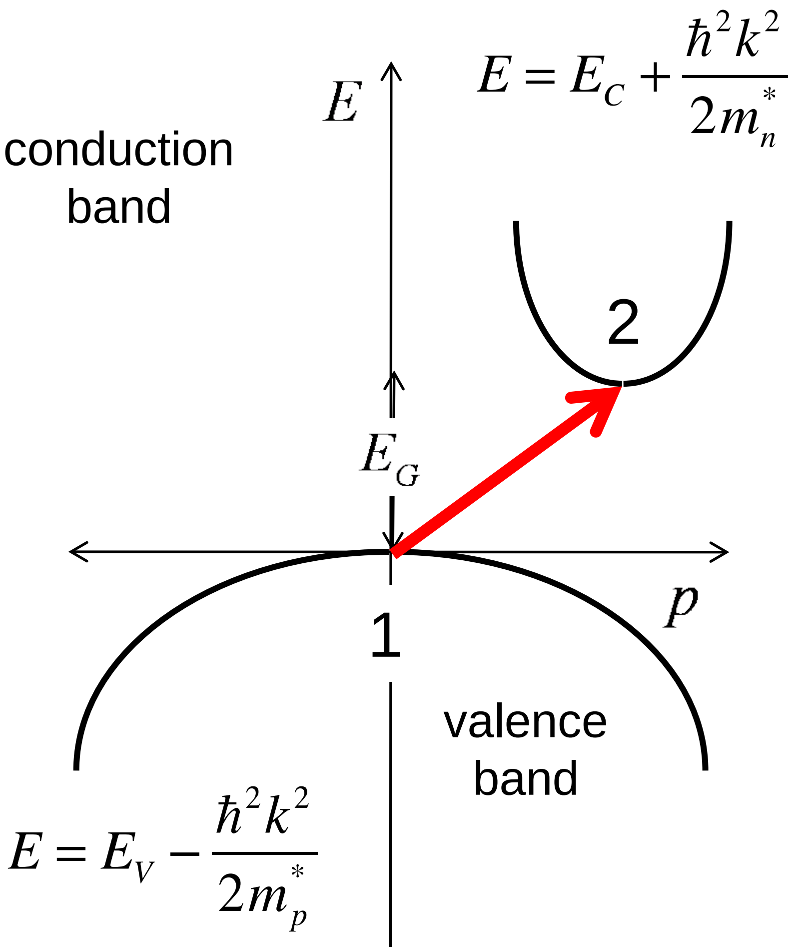
Conservation of momentum:

$$\hbar k_1 - \hbar k_2 = \hbar k_{ph} \approx 0$$

$$k_1 \approx k_2$$

("vertical transitions" because photons have very little momentum)

Optical absorption in an **indirect gap** semiconductor



Conservation of energy:

$$E_{ph} = hf \approx E_G \pm \hbar\omega_{lv}$$

Conservation of momentum:

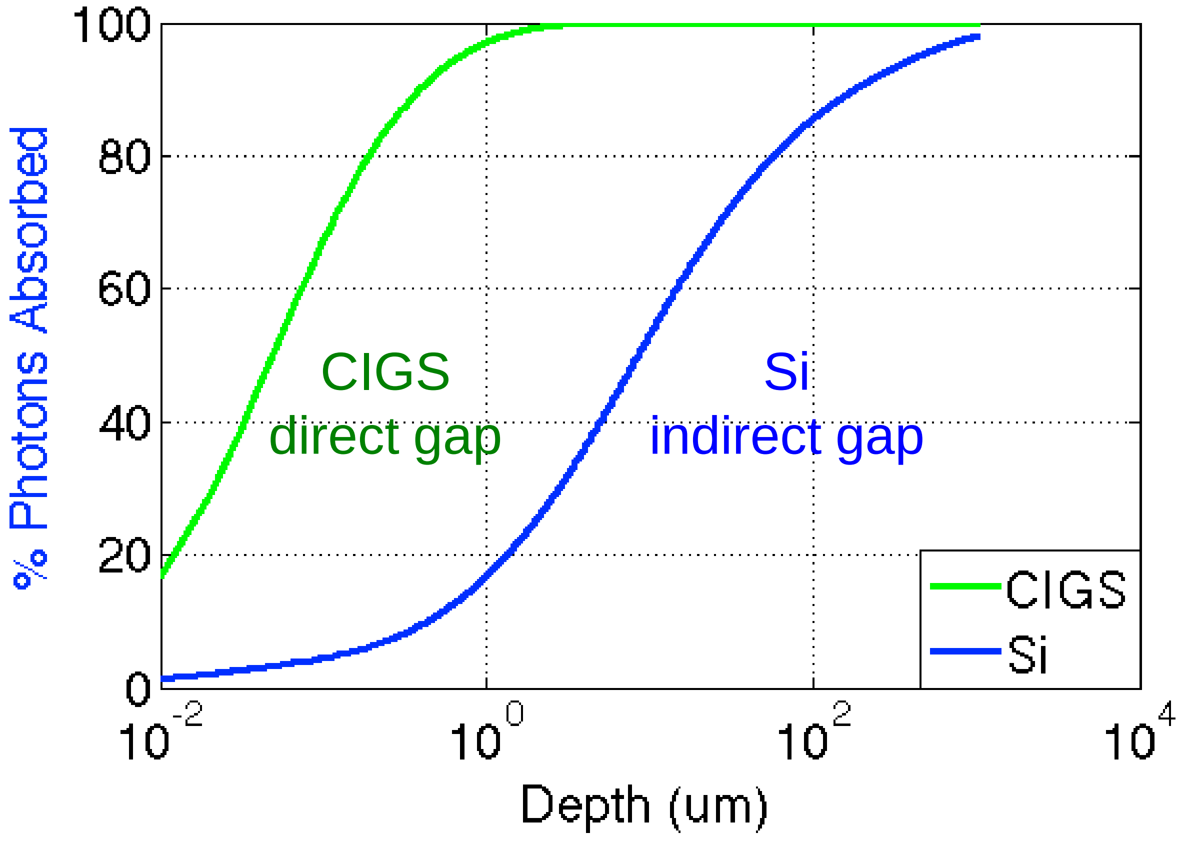
$$\hbar k_1 - \hbar k_2 = \hbar k_{ph} + \hbar k_{lv}$$

(must involve a lattice vibration with the right momentum)

BB absorption in indirect semiconductors is very weak!

Optical absorption vs. semiconductor thickness

The direct bandgap of CIGS (Copper Indium Gallium Selenide) allows it to absorb light much faster than Silicon. A layer of silicon must be 10^4 microns thick to absorb ~100% of the light, while CIGS need only be about 2 microns thick.



Absorption coefficient

Incident flux: Φ_0

Flux at position, *x* : $\Phi(x) = \Phi_0 e^{-\alpha(\lambda)x}$

optical absorption coefficient:

$$\alpha(\lambda) > 0 \quad \text{for} \quad E > E_G \left(\lambda < hc/E_G\right)$$

Generation rate at position, *x*

:

$$G(x) = -\frac{d\Phi(x)}{dx} = \Phi_0 \alpha(\lambda) e^{-\alpha(\lambda)x}$$

$$\alpha(\lambda)$$

Types of generation

1) Optical generation

"Inverse of radiative recombination"

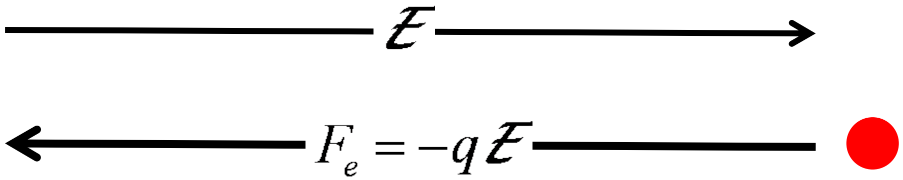
2) Thermal generation

"Inverse of SRH recombination"

3) Impact ionization

"Inverse of Auger recombination"

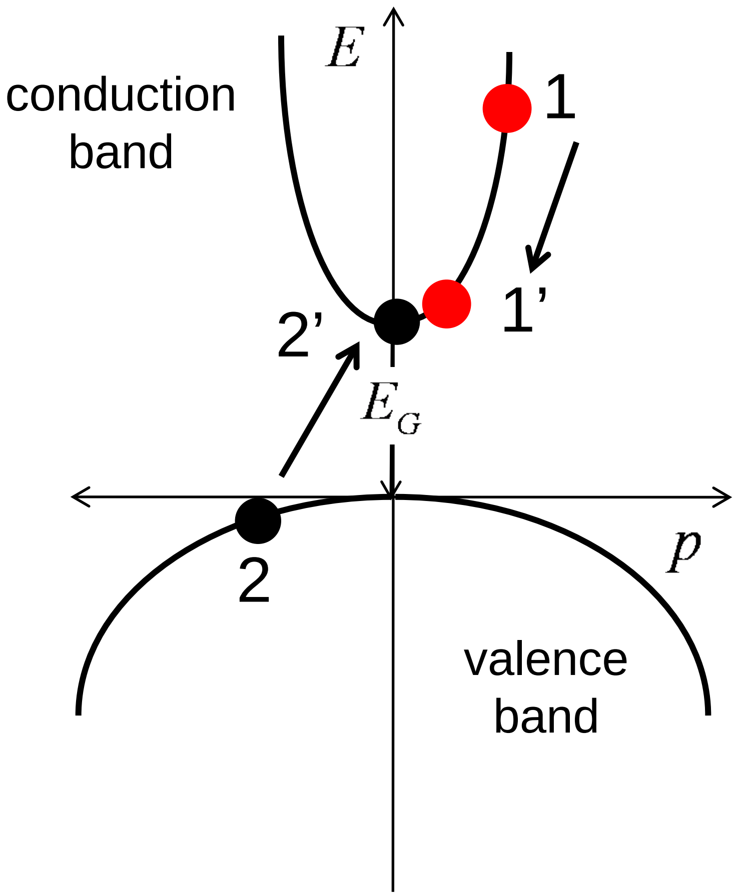
Impact ionization



Under large electric fields, electrons can gain a lot of kinetic energy.

If the kinetic energy exceeds the band gap, then a collision with an atom in the lattice can produce and electron and hole.

Impact ionization: $E(k)$ picture



Energetic electron 1 produces and e-h pair, 2 and 2'

Electrons 1' and 2' can now gain energy in the strong electric field, and produce 2 more e-h pairs.

As the process continues, the number of e-h pairs multiplies.

Impact ionization

The process we have described is called **avalanche multiplication** and can lead to “breakdown” in semiconductor devices under high voltages.

Wider bandgap semiconductors have less impact ionization and, therefore, higher breakdown voltages.

Avalanche multiplication is also used to produce sensitive photodetectors – avalanche photodetectors.

Generation

1) Optical generation

Inverse of radiative recombination

2) Thermal generation

Inverse of SRH recombination

3) Impact ionization

Inverse of Auger recombination