University of Michigan – Shanghai Jiao Tong University Joint Institute
Center of Optics and Optoelectronics

VE 320 – Summer 2012
Introduction to Semiconductor Device

Recombination and Generation

Instructor: Professor Hua Bao

Generation and Recombination

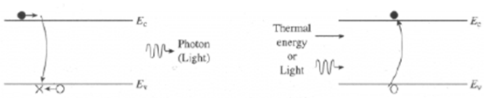
Generation : creation of conducting electrons and holes

Recombination: elimination of conducting electrons and holes

There are several physical processes where G-R may occur

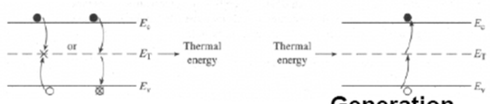
R-G Process

Band-to-Band



Recombination **Generation**

R-G Center



Recombination **Generation**

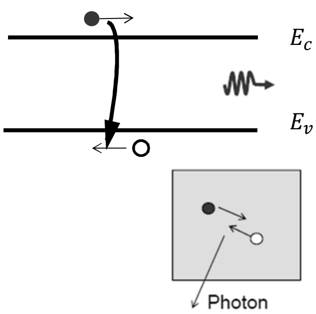
Auger

(a.k.a. impact ionization)

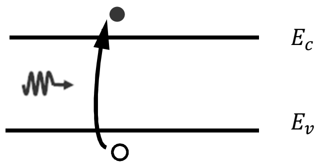
Recombination **Generation**

Band to Band

Recombination



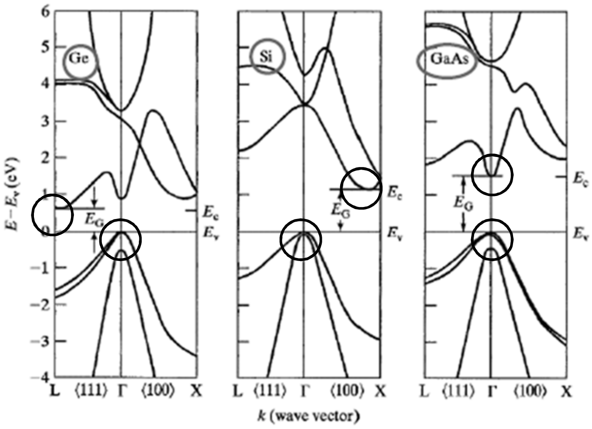
Generation



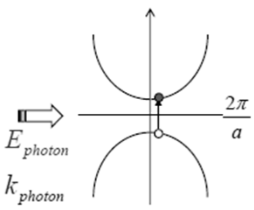
- **Band to Band or "direct" (directly across the band) generation**
- **Basis for optoelectronic devices such as light-emitting diodes, photodetectors, solar cells, etc…**

A Little More Details

Direct and Indirect Band Gap



Photon Energy and Wave Vector



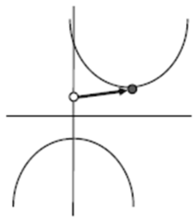
$$E_V + E_{photon} = E_C$$

$$\hbar k_V + \hbar k_{photon} = \hbar k_C$$

$$k_{photon} = \frac{2\pi}{\lambda \text{ in } \mu\text{m}} = \frac{2\pi}{1.21/E_{photon} \text{ in eV}} \boxed{<< \frac{2\pi}{a} = \frac{2\pi}{5\times10^{-4}\ \mu\text{m}}}$$

Photon has large energy for excitation through bandgap, but its wavevector is negligible compared to size of BZ

Phonon Energy and Wave Vector



$$E_V + E_{phonon} = E_C$$

$$\hbar k_V + \hbar k_{phonon} = \hbar k_C$$

$$k_{phonon} = \frac{2\pi}{\lambda} = \frac{2\pi}{\hbar \upsilon_{sound} / E_{phonon}} \approx \frac{2\pi}{a} = \frac{2\pi}{5\times10^{-4}\ \mu\mathrm{m}}$$

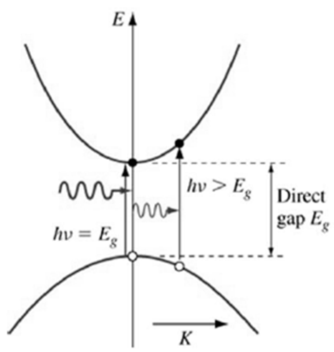
Phonon has large wavevector comparable to BZ, but negligible energy compared to bandgap

Optical Generation

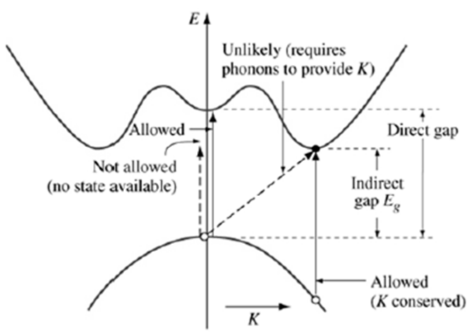
Both energy and momentum conservation needs to be satisfied.

The momentum of a photon is small

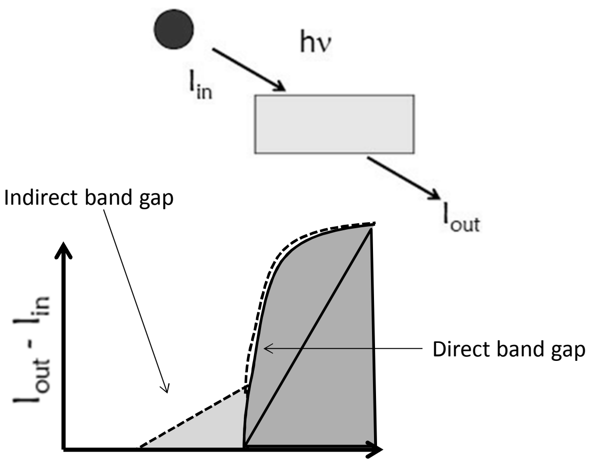
Direct Bandgap (e.g. GaAs)



Indirect Bandgap (e.g. Si)

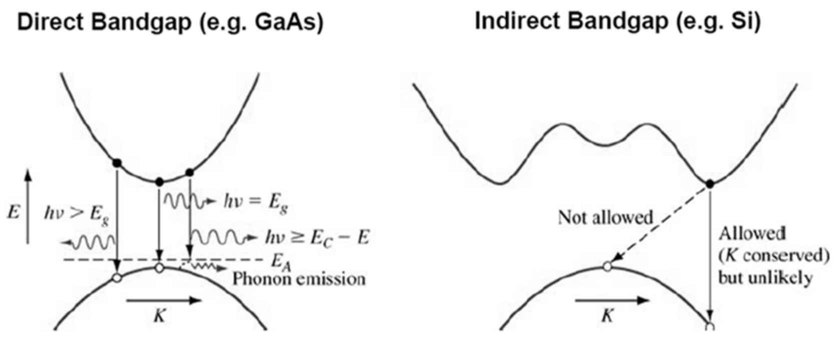


Absorption



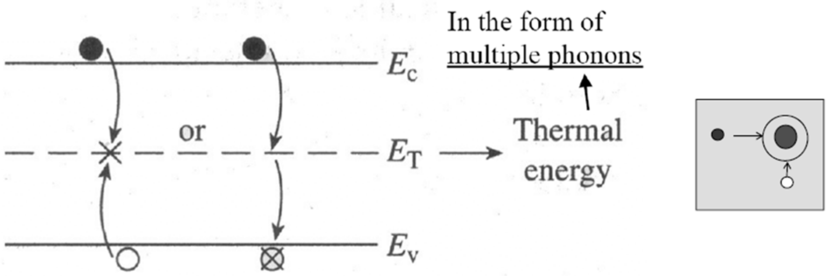
Optical Recombination

The momentum of a photon is small



Would you expect radiative recombination (light emission) to be significant in silicon?

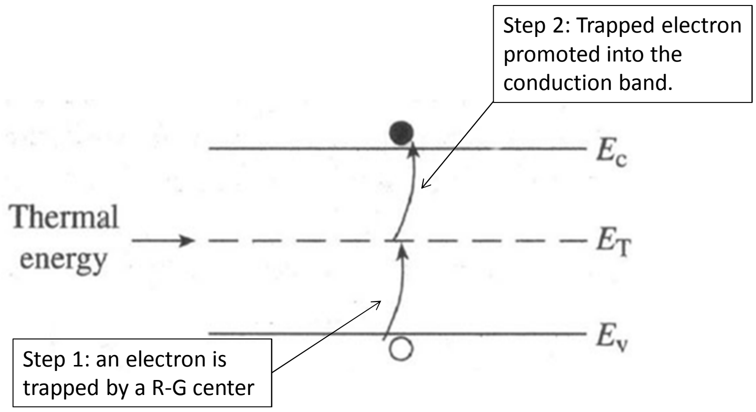
R-G Center Recombination



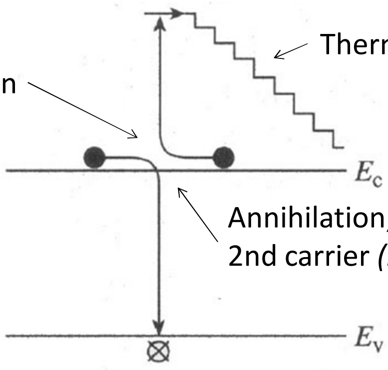
•**Recombination-Generation (R-G) Center recombination.**

•**Two steps: 1.) 1st carrier is "trapped" (localized) at an impurity (trap) site. 2.) 2nd carrier (opposite type) is attracted to the R-G center and annihilates the 1st carrier.**

R-G Center Generation

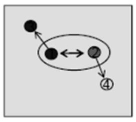


Auger Recombination

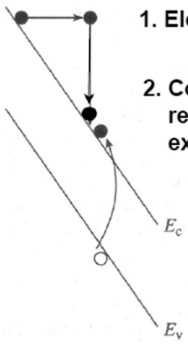


Before: 2 conduction electron + 1 hole
After: 1 high energy conduction electron

More common in heavily doped devices



Impact Ionization



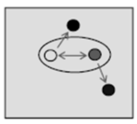
1. Electron gains enough K.E.

2. Collides with a lattice atom releases K.E. excites an *e-h* pair

Reverse process of Auger Recombination

Before: 1 high energy conduction electron
After: 2 conduction electrons + 1 hole

More common in high $\mathcal{E}$ conditions



R-G Rate

Typically, one mechanism occurs at a much faster rate and is dominant

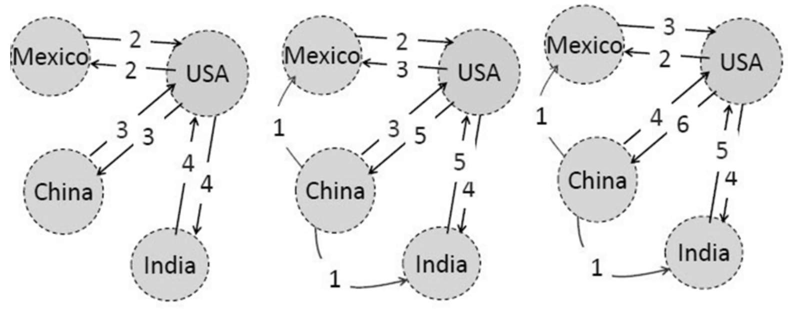
$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i}$$

For Si, typically only needs to consider two R-G processes:

- **R-G via R-G centers (also called indirect thermal R-G).**
- **Photongeneration (if light is shined on the sample).**

Equilibrium, Transient, Steady-State

At equilibrium, detailed balance must be satisfied.

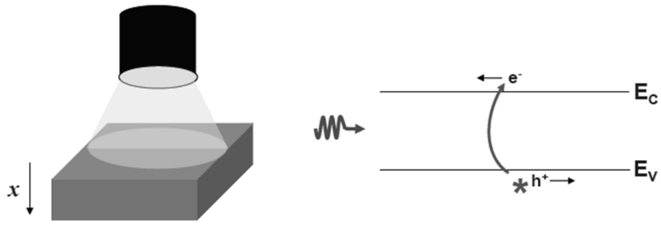


9 in 9 out
Population conserved

Forced unidirectional connections (red lines) disturbs equilibrium (e.g. 9 in/12 out at time t1 local populations not conserved, but global population is ....

12 in 12 out
Population stabilized

Photo Generation



- **Intensity of Light in the Semiconductor:** $I = I_0 e^{-\alpha(\lambda)x}$
- **Generation is one-to-one with Light Absorption**
- **Generation Rate:** $G_L(x,\lambda) = G_{L0}e^{-\alpha x}$

$$\frac{\partial n}{\partial t}|_{light} = \frac{\partial n}{\partial t}|_{light} = G_L(x,\lambda)$$

Low-level Injection

n_0, p_0	...	carrier concentrations in the material under analysis when equilibrium conditions prevail.
n, p	...	carrier concentrations in the material under arbitrary conditions.
$\Delta n \equiv n - n_0$ $\Delta p \equiv p - p_0$	...	deviations in the carrier concentrations from their equilibrium values. Δn and Δp can be both positive and negative, where a positive deviation corresponds to a carrier excess and a negative deviation corresponds to a carrier deficit.

n= Δ n+n$_0$ and p= Δ p+p$_0$

Δn=Δp ⟺ electrons/holes created/annihilated in pairs

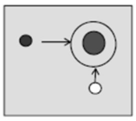
$\boxed{\textit{In non-equilibrium, np may not equal } n_i^2}$

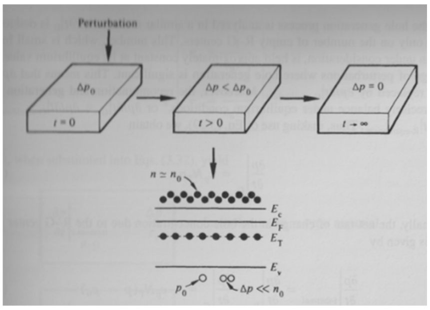
Low-level Injection:

- **$\Delta p \ll n_0$ $n \approx n_0$ n-type material**
- **$\Delta n \ll p_0$ $p \approx p_0$ p-type material**

Indirect Thermal R-G

N_T ~ Number of traps





Recombination Process

$$\frac{\partial p}{\partial t}|_R = -c_p N_T p$$

At equilibrium, R and G processes must be balanced: $\frac{\partial p}{\partial t}|_G = -c_p N_T p_0$

Net R-G process: $\frac{\partial p}{\partial t}|_G = -c_p N_T (p - p_0) = -c_p N_T \Delta p$

Indirect Thermal R-G

Define $\tau_p = \frac{1}{c_p N_T}$

$$\frac{\partial p}{\partial t}\Big|_{\substack{i-thermal \\ R-G}} = -\frac{\Delta p}{\tau_p}$$

Similarly

$$\frac{\partial n}{\partial t}\Big|_{\substack{i-thermal \\ R-G}} = -\frac{\Delta n}{\tau_n}$$

Applicable only to **minority carriers and low-level injection** condition must be satisfied!

Carrier Behavior

We have determined carrier processes

- Drift
- Diffusion
- Generation and Recombination

The development of relationships between these processes will provide a basis to solve device problems.