

# Excess Carriers in Semiconductors

Most semiconductor devices operate by the creation of charge carriers in excess of the thermal equilibrium values. (thermal equilibrium values are for eg. in n type SC  $n_0 = N_d$  &  $p_0 = \frac{n_i^2}{N_d}$  ).

These excess carriers can be created by optical excitation or electron bombardment, or they can be injected across a forward-biased p-n junction.

However the excess carriers can dominate the conduction processes in the semiconductor material.

# Optical Absorption

- An important technique for measuring the band gap energy of a semiconductor is the absorption of incident photons by the material.
- Since photons with energies greater than the band gap energy are absorbed while photons with energies less than the band gap are transmitted, which gives an accurate measure of the band gap energy.
- Photon with energy  $h\nu \geq E_g$  can be absorbed in a semiconductor.
- Since the valence band contains many electrons and the conduction band has many empty states into which the electrons may be excited, the probability of photon absorption is high

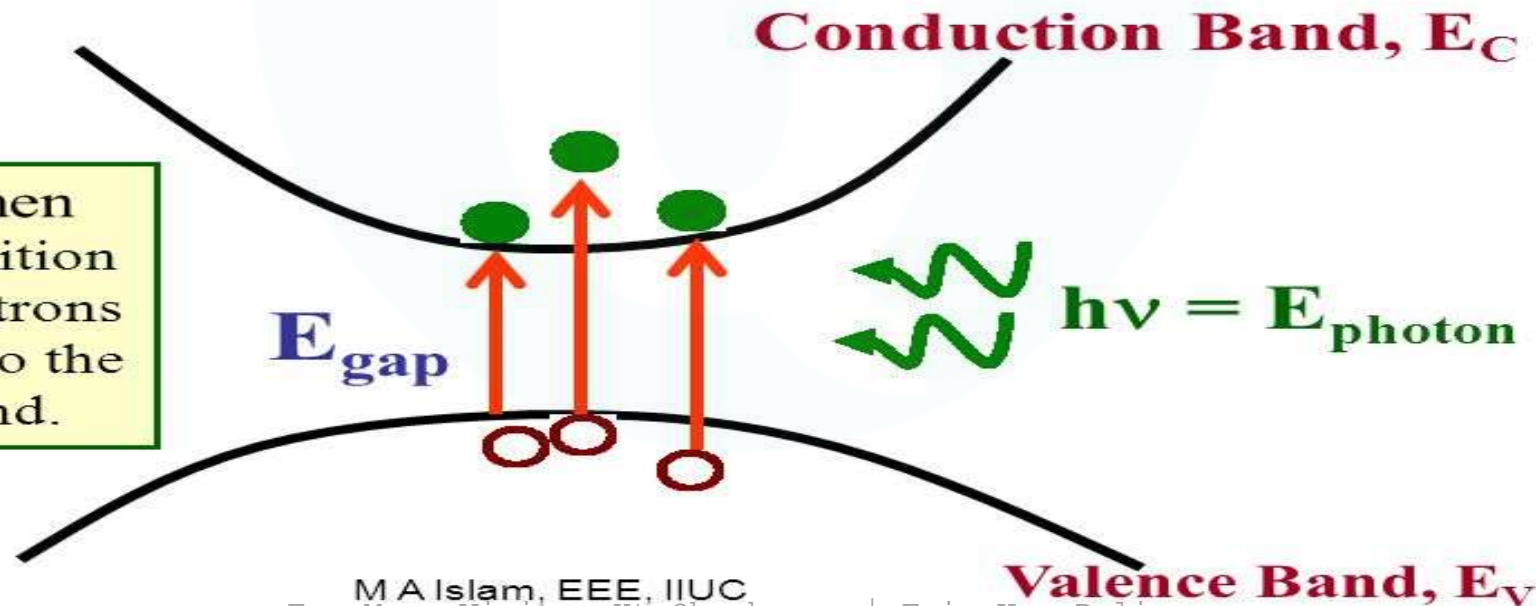
# Generation of excess hole electron pairs.

## Valence Band – Conduction Band Absorption (Band to Band Absorption)

This process obviously requires that the minimum energy of a photon to initiate an electron transition must satisfy

$$E_C - E_V = h\nu = E_{\text{gap}}$$

If  $h\nu > E_{\text{gap}}$  then obviously a transition can happen. Electrons are then excited to the conduction band.



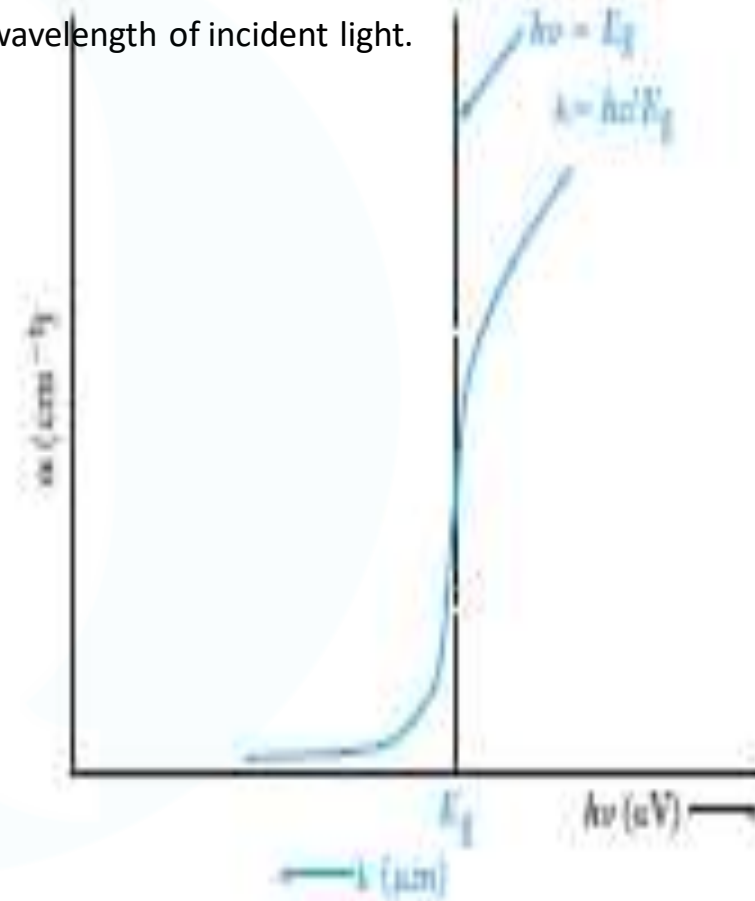
# Optical Absorption

- The electron and hole created by this absorption process are *excess carriers*;
- since they are out of balance with their environment, they must eventually recombine.
- While the excess carriers exist in their respective bands, however, they are free to contribute to the conductivity of the material.

# Generation of excess hole electron pairs.

- A photon with energy less than  $E_g$  is unable to excite an electron from the valence band to the conduction band. Thus photons with  $h\nu < E_g$  ( $\nu = \frac{c}{\lambda}$ ,  $h \frac{c}{\lambda} < E_g$ ,  $\lambda > \frac{hc}{E_g}$ ) will pass through unabsorbed.
- While photons with energy  $h\nu > E_g$  ( $\nu = \frac{c}{\lambda}$ ,  $h \frac{c}{\lambda} > E_g$ ,  $\lambda < \frac{hc}{E_g}$ ) will excite an electron from the valence band to the conduction band, thus EHPs are generated & the excess energy ( $E_g - h\nu$ ) will be absorbed as heat. This excess EHPs will increase conductivity.
- While  $\nu = \frac{c}{\lambda}$ ,  $h \frac{c}{\lambda} = E_g$ , therefore  $\lambda = \frac{hc}{E_g}$ .

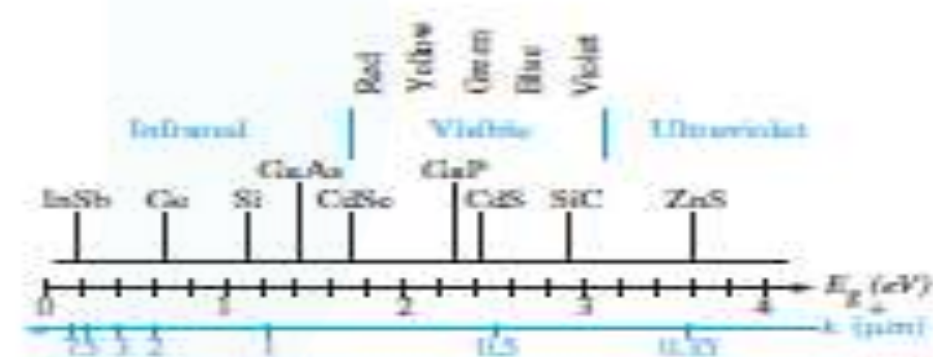
- Dependence of optical absorption coefficient  $\alpha$  for a semiconductor on the wavelength of incident light.



# Generation of excess hole electron pairs.

Here shows band gaps of some common semiconductors relative to the visible, infrared, and ultraviolet portions of the optical spectrum. Common semiconductors GaAs, Si, Ge, and InSb lie outside the visible region, in the infrared.

Other semiconductors, such as GaP and CdS, have band gaps wide enough to pass photons in the visible range. It is important to note here that a semiconductor absorbs photons with energies equal to the band gap, or larger.



- One can measure  $E_g$  in this fashion.

# Generation of excess hole electron pairs.

- The intensity of light transmitted through the sample thickness  $l$  is
- $I_t = I_0 e^{-\alpha l}$ . The coefficient  $\alpha$  is called the *absorption coefficient* and has units
- of  $\text{cm}^{-1}$ . This coefficient will of course vary with the photon wavelength
- and with the material. In a typical plot of  $\alpha$  vs.  $\lambda$  wavelength there is negligible absorption at long wavelengths ( $h\nu$  small) and considerable
- absorption of photons with energies larger than  $E_g$ .
- The relation between photon energy and wavelength is  $E_g = hc / \lambda$ . If  $E$  is given in electron volts and  $\lambda$  in micrometers, this becomes  $E_g = 1.24 / \lambda$ .

# *Photoluminescence*

- When electron– hole pairs are generated in a semiconductor, or when carriers are excited into higher impurity levels from which they fall to their equilibrium states, light can be given off by the material. Many of the semiconductors are well suited for light emission, particularly the compound semiconductors with direct band gaps. The general property of light emission is called *luminescence*.
- This overall category can be subdivided according to the excitation mechanism: If carriers are excited by photon absorption, the
- radiation resulting from the recombination of the excited carriers is called *photoluminescence*;



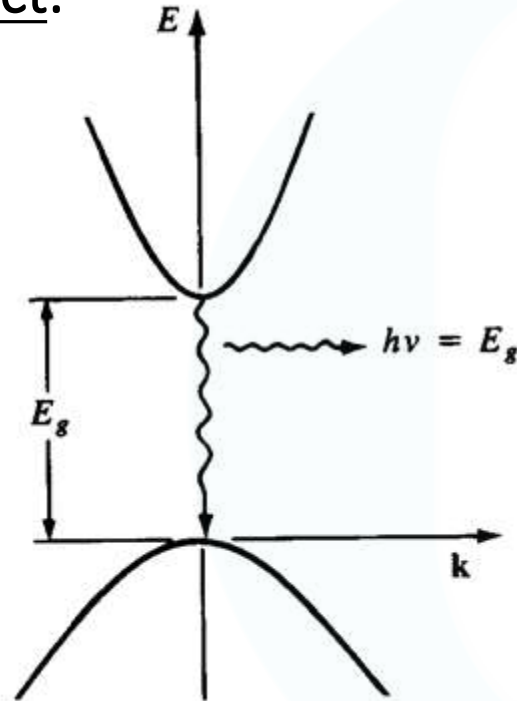
# *Cathodo & electroluminescence*

- if the excited carriers are created by high- energy electron bombardment of the material, the mechanism is called *cathodoluminescence*;
- if the excitation occurs by the introduction of current into the sample, the resulting luminescence is called *electroluminescence*.
- Other types of excitation are possible, but these three are the most important for device applications.

# Direct vs. Indirect Band Gap Materials

Energy ( $E$ ) vs. momentum ( $\hbar k$ ) Diagrams

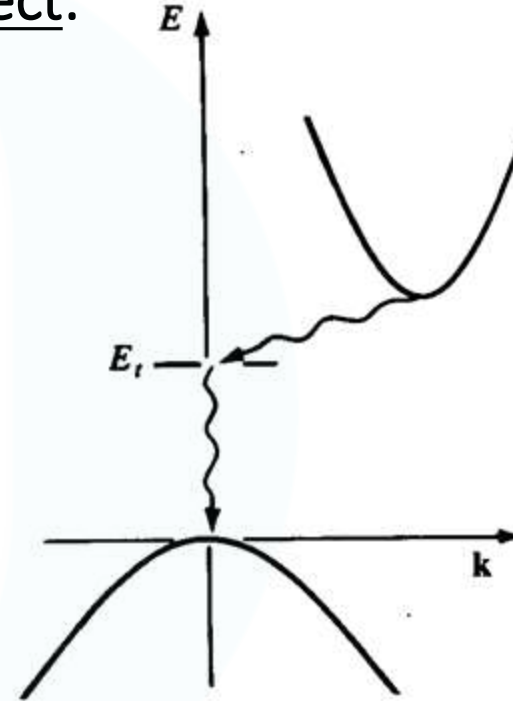
Direct:



Little change in momentum is required for recombination

→ momentum is conserved by photon emission

Indirect:



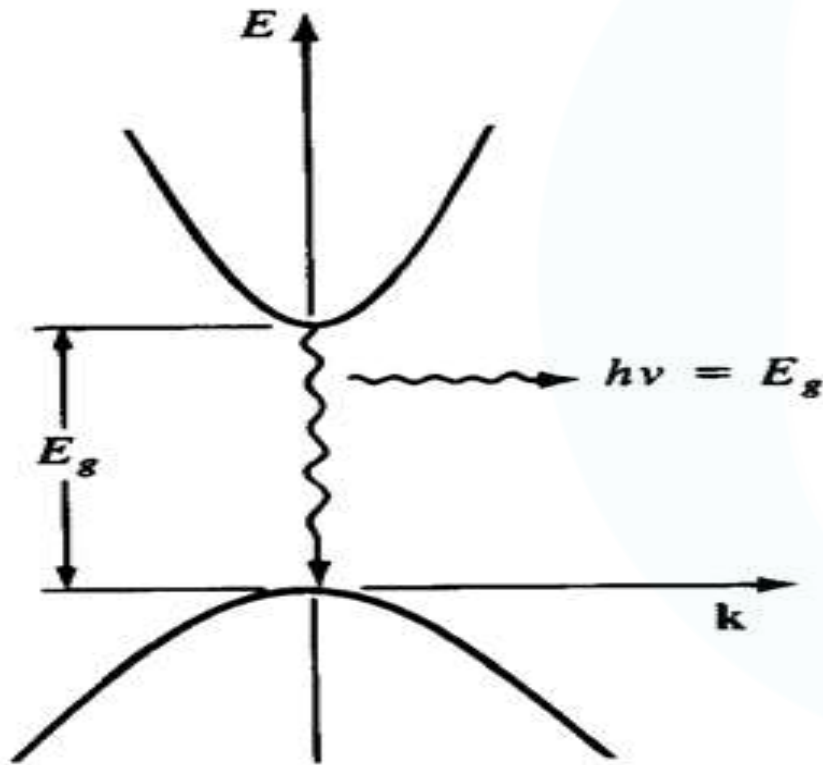
Large change in momentum is required for recombination

→ momentum is conserved by phonon + photon emission

# Carrier Lifetime and Photoconductivity

- When excess electrons and holes are created in a semiconductor, there is a corresponding increase in the conductivity of the sample.
- If the excess carriers arise from optical luminescence, the resulting increase in conductivity is called *photoconductivity*.
- This an important effect-an useful application in the analysis of semiconductor materials & in the operation of several types of photoconductive devices.
- Also we have to examine the mechanisms by which excess electrons and holes recombine to the analysis of photoconductive devices.

# Direct Recombination of Electrons and Holes



- Electrons in the conduction band of a semiconductor may make transitions to the valence band (i.e., recombine with holes in the valence band) either directly or indirectly.
- In direct recombination, an excess population of electrons and holes decays by electrons falling from the conduction band to empty states (holes) in the valence band. Energy lost by an electron in making the transition is given up as a photon.
- Direct recombination occurs *spontaneously*; that is, the probability that an electron and a hole will recombine is constant in time.

# Direct Recombination of Electrons and Holes

- The constant probability leads us to expect an exponential solution for the decay of the excess carriers. In this case the rate of decay of electrons at any time  $t$  is proportional to the number of electrons remaining at  $t$  and the number of holes, with some constant of proportionality for recombination,  $\alpha_r$ .
- The *net* rate of change in the conduction band electron concentration is the thermal generation rate  $\alpha_r n_i^2$  minus the recombination rate
- $$\frac{dn(t)}{dt} = \alpha_r n_i^2 - \alpha_r n(t)p(t)$$

# Direct Recombination of Electrons and Holes

- Let us assume the excess electron– hole population is created at  $t = 0$ , for example by a short flash of light, and the initial excess electron and hole concentrations  $\Delta n$  and  $\Delta p$  are equal.
- Then as the electrons and holes recombine in pairs, the instantaneous concentrations of excess carriers  $\Delta n(t)$  and  $\Delta p(t)$  are also equal. Thus we can write the total concentrations in terms of the equilibrium values  $n_0$  and  $p_0$  and the excess carrier concentrations
- $\delta n(t) = \delta p(t)$ .
- we have 
$$d\frac{\delta n(t)}{dt} = \alpha_r n_i^2 - \alpha_r [n_0 + \delta n(t)][p_0 + \delta p(t)]$$
- $$= \alpha_r n_i^2 - \alpha_r [n_0 p_0 + [n_0 + p_0]\delta n(t) + \delta n^2(t)]$$
  
 $(\alpha_r n_i^2 = \alpha_r n_0 p_0, \text{generation rate} = \text{recombination rate equilibrium condition})$

$$d\frac{\delta n(t)}{dt} = - \alpha_r [[n_0 + p_0]\delta n(t) + \delta n^2(t)]$$

# Direct Recombination of Electrons and Holes- Low level Injection

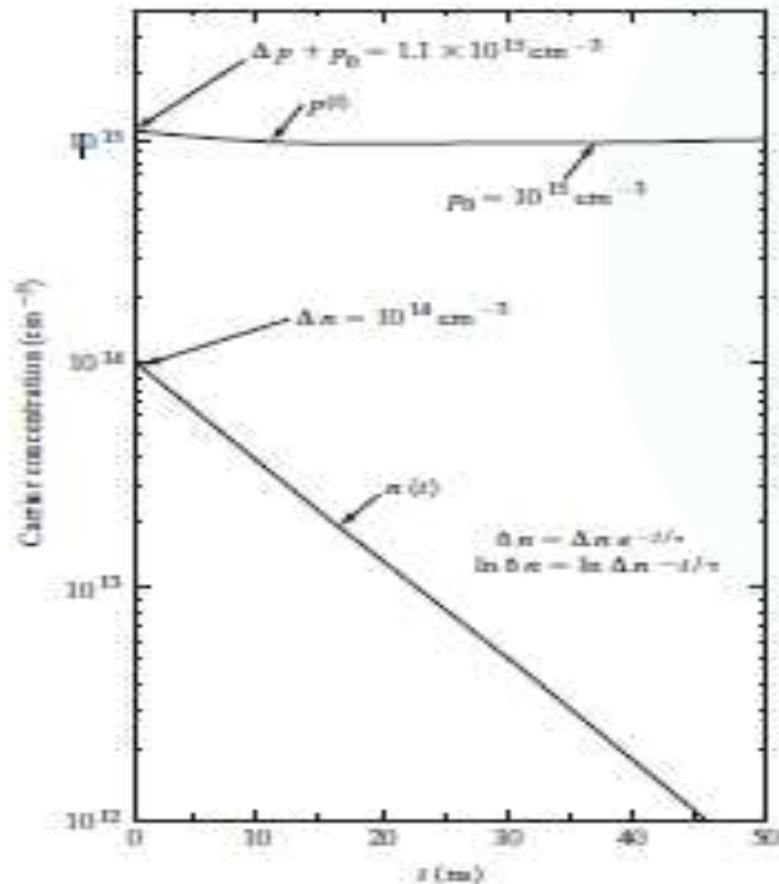
- This nonlinear equation would be difficult to solve in its present form.
- But if we assume **low-level injection** ie. if the excess carrier concentrations are small, we can neglect the  $\delta n^2$  term. Furthermore, if the material is extrinsic, we can usually neglect the term representing the equilibrium minority carriers. For example, if the material is p- type ( $p_0 \gg n_0$ ) .Then the equation becomes
- $\frac{d\delta n(t)}{dt} = -\alpha_r p_0 \delta n(t)$
- The solution to this equation is an exponential decay from the original excess carrier concentration  $\Delta n$ :
- $\delta n(t) = \Delta n e^{-\alpha_r p_0 t} = \Delta n e^{-t/\tau_n}$  . Excess electrons in a p- type semiconductor recombine with a decay constant  $\tau_n = (\alpha_r p_0)^{-1}$ , called the *recombination lifetime*.

# Direct Recombination of Electrons and Holes- *minority carrier lifetime*

- Since the calculation is made in terms of the minority carriers,  $\tau_n$  is often called the *minority carrier lifetime*. The decay of excess holes in n-type material occurs with  $\tau_p = (\alpha_r n_0)^{-1}$ . In the case of direct recombination, the excess majority carriers decay at exactly the same rate as the minority carriers.
- There is a large percentage change in the minority carrier electron concentration & a small percentage change in the majority hole concentration.
- Basically, the approximations of extrinsic material and low-level injection allow us to represent  $n(t)$  by the excess concentration  $\delta n(t)$  and  $p(t)$  by the equilibrium value  $p_0$ .
- A more general expression for the carrier lifetime is  $\tau_n = \frac{1}{\alpha_r (n_0 + p_0)}$ . This expression is valid for n- or p- type material if the injection level is low.



# Direct Recombination of Electrons and Holes- *minority carrier lifetime*

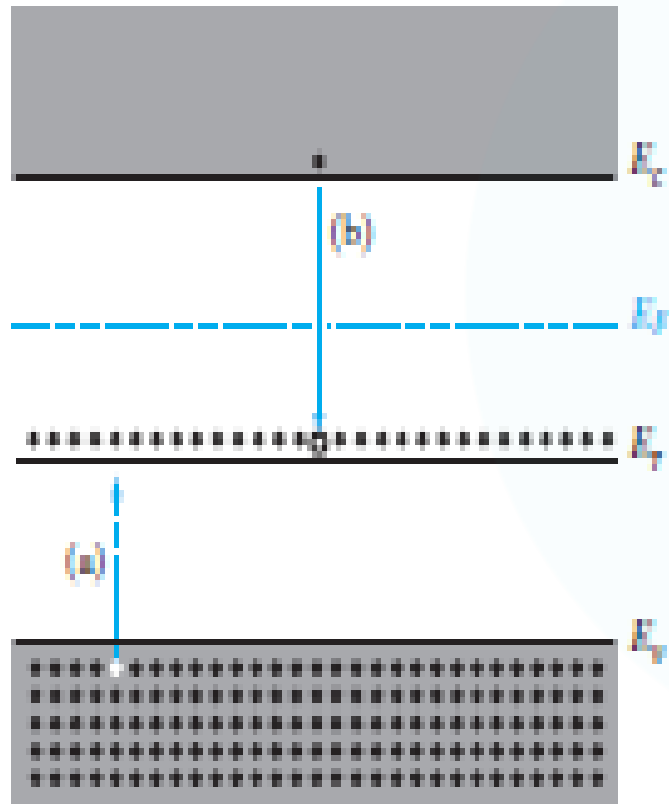


- Decay of excess electrons and holes by recombination, for  $\Delta n = \Delta p = 0.1p_0$ , with  $n_0$  negligible, and  $\tau = 10 \text{ ns}$ . The exponential
- decay of  $dn(t)$  is linear on this
- semilogarithmic graph. (A sample of GaAs is doped with  $10^{15}$  acceptors/ $\text{cm}^3$ . The intrinsic carrier concentration of GaAs is approximately  $10^6 \text{ cm}^{-3}$ ; thus the minority electron concentration is  $n_0 = \frac{n_i^2}{p_0} = 10^{-3} \text{ cm}^{-3}$
- The approximation of  $p_0 \gg n_0$  is valid in this case. Now if  $10^{14} \text{ EHP/cm}^3$  are created at  $t = 0$  the graph shows the decay of these carriers in time.

# Indirect Recombination; Trapping

- In column IV semiconductors and in certain compounds, the probability of direct electron– hole recombination is very small . There is some band gap light given off by materials such as Si and Ge during recombination, but this radiation is very weak and may be detected only by sensitive equipment.
- The vast majority of the recombination events in indirect materials occur via *recombination levels* within the band gap, and the resulting energy loss by recombining electrons is usually given up to the lattice as heat rather than by the emission of photons.
- Any impurity or lattice defect can serve as a recombination center if it is capable of receiving a carrier of one type and subsequently capturing the opposite type of carrier, thereby annihilating the pair.

# Indirect Recombination; Trapping



- Fig illustrates a recombination level
- $E_r$  which is below  $E_f$  at equilibrium and therefore is substantially filled with electrons. When excess electrons and holes are created in this material, each EHP recombines at  $E_r$  in two steps: (a) hole capture and (b) electron capture.
- Capture processes at a recombination level: (a) hole capture at a filled recombination center; (b) electron capture at an empty center.

# Indirect Recombination; Trapping

- Since the recombination centers are filled at equilibrium, the first event in the recombination process is hole capture i.e. an electron at  $E_r$  falling to the valence band, leaving behind an empty state in the recombination level. Thus in hole capture, energy is *given up* as heat to the lattice.
- Similarly, in electron capture -energy is given up when a conduction band electron subsequently falls to the empty state in  $E_r$ .
- When both of these events have occurred, the recombination center is back to its original state (filled with an electron), but an EHP is missing. Thus one EHP recombination has taken place, and the center is ready to participate in another recombination event by capturing a hole.

# Indirect Recombination; Trapping

- The carrier lifetime resulting from indirect recombination is somewhat more complicated than is the case for direct recombination, since it is necessary to account for unequal times required for capturing each type of carrier
- Sometimes when a carrier is trapped temporarily at a center and then is reexcited without recombination taking place, the process is often called *temporary trapping*

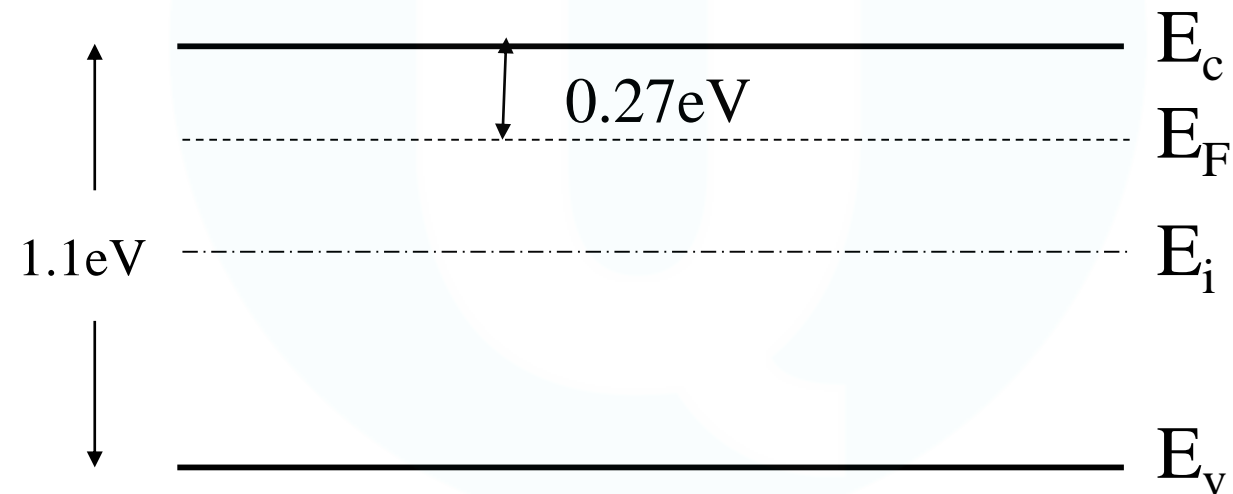
# Assignment Qns

- Calculate the thermal equilibrium electron and hole concentration in silicon at  $T=300\text{K}$ , when the Fermi energy level is  $0.27\text{ eV}$  below the conduction band edge  $E_C$ . The effective densities of states in the conduction band and valence band are  $2.8 \times 10^{19}\text{ cm}^{-3}$  and  $1.04 \times 10^{19}\text{ cm}^{-3}$  respectively at  $300\text{K}$ .
- For the given data, calculate hole and intrinsic carrier concentrations. Also sketch the band diagram.  $N_C = 10^{19}\text{ cm}^{-3}$ ,  $N_V = 5 \times 10^{18}\text{ cm}^{-3}$ ,  $E_g = 2\text{ eV}$ ,  $T = 900\text{K}$ ,  $n_0 = 10^{17}\text{ cm}^{-3}$
- The Fermi level position in a Si sample at  $300\text{K}$  is  $0.29\text{ eV}$  below  $E_C$ . Determine the carrier concentration of the specimen. Given that  $n_i = 1.5 \times 10^{10}\text{ cm}^{-3}$ .

$$n_0 = N_c e^{-(E_C - E_F)/kT} \quad p_0 = N_v e^{-(E_F - E_V)/kT}$$

# Electron and Hole Concentrations at Equilibrium

□ Answer (Continue) :





# Steady State Carrier Generation; Quasi-Fermi Levels

- For example, a semiconductor at equilibrium experiences thermal generation of EHPs at a rate  $g(T) = g_i$ . This generation is balanced by the recombination rate so that the equilibrium concentrations of carriers  $n_0$  and  $p_0$  are maintained:
- $g(T) = \alpha_r n_i^2 = \alpha_r n_0 p_0$ , generation rate = recombination rate.
- If a steady light is shone on the sample, an optical generation rate  $g_{op}$  will be added to the thermal generation, and the carrier concentrations  $n$  and  $p$  will increase to new steady state values.
- $g(T) + g_{op} = \alpha_r np = \alpha_r [n_0 + \delta n][p_0 + \delta p]$

# Steady State Carrier Generation; excess concentration

- For steady state recombination and no trapping,  $\Delta n = \Delta p$ ; thus
- $g(T) + g_{op} = \alpha_r n_0 p_0 + \alpha_r [(n_0 + p_0) \delta_n + \delta_n^2]$  (low-level injection ie. if the excess carrier concentrations are small, we can neglect the  $\delta n^2$  term &  $g(T) = \alpha_r n_0 p_0$ , generation rate = recombination rate equilibrium condition)
- $g_{op} = \alpha_r [(n_0 + p_0) \delta n = \frac{\delta_n}{\tau_n}]$
- $\delta n = g_{op} \times \tau_n$

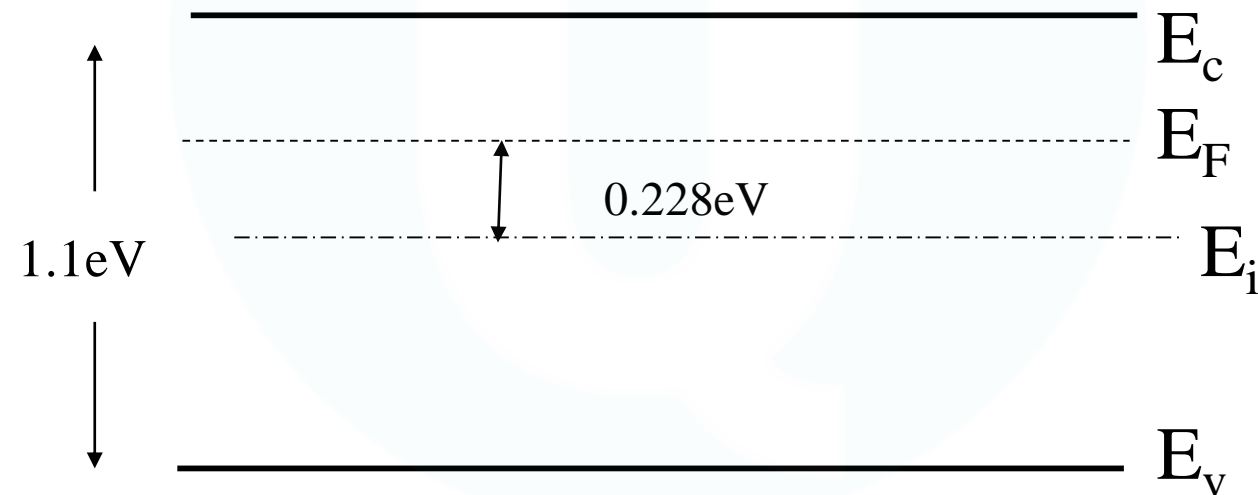
# Steady State Carrier Generation; Quasi-Fermi Levels

- Question : Let us assume that  $10^{13}$  EHP/cm<sup>3</sup> are created optically every microsecond in a Si sample with  $n_0 = 10^{14}$  cm<sup>-3</sup> and  $\tau_n = \tau_p = 2$   $\mu$ s.
- In this example, the equilibrium Fermi level is  $0.0259 \ln(6.67 * 10^3) = 0.228$  eV above the intrinsic level,

$$E_f - E_i = kT \ln \frac{n_0}{n_i} = 0.0259 \ln \frac{10^{14}}{1.5 \times 10^{10}} = 0.228 eV$$

# Electron and Hole Concentrations at Equilibrium

□ Answer (Continue) :



# Steady State Carrier Generation; Quasi-Fermi Levels

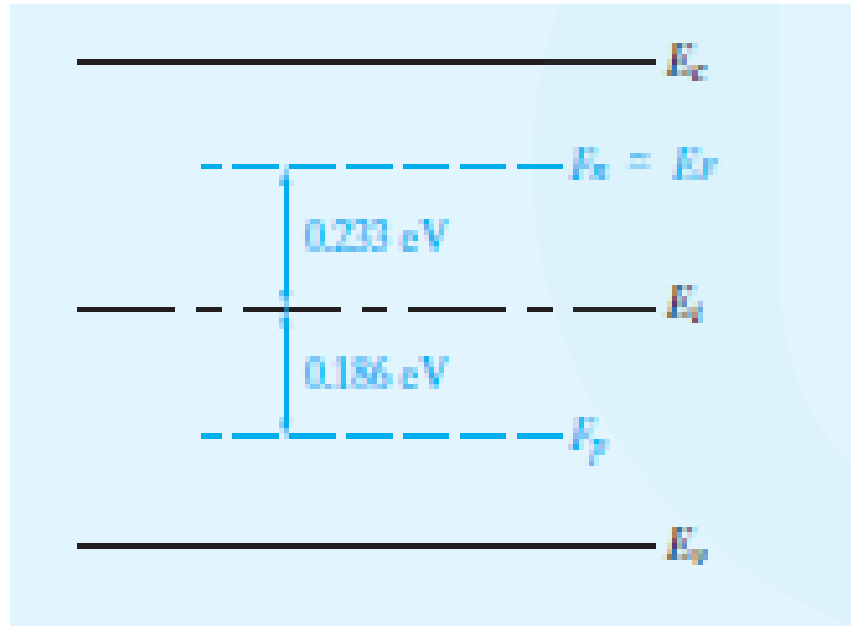
- Now  $10^{13}$  EHP/cm<sup>3</sup> are created optically every microsecond in a Si sample (with  $n_0 = 10^{14}$  cm<sup>-3</sup>) and  $\tau_n = \tau_p = 2$   $\mu$ s.
- The steady state excess electron (or hole) concentration is then  $\delta p = g_{op} \times \tau_p = 2 \times 10^{13}$  cm<sup>-3</sup>.
- While the percentage change in the majority electron concentration is small, the minority carrier concentration changes from  $p_0 = \frac{n_i^2}{n_0} = \frac{2.25 \times 10^{20}}{10^{14}} = 2.25 \times 10^6$  cm<sup>-3</sup>
- to  $p = 2 \times 10^{13}$  cm<sup>-3</sup> (*steady state*).
- Note that the equilibrium equation cannot be used.  $n_0 p_0 = n_i^2$
- with the subscripts removed; that is,  $np \neq n_i^2$

when excess carriers are present.

# Steady State Carrier Generation; Quasi-Fermi Levels

- The steady state electron concentration is
- $n = n_0 + \delta n = 10^{14} + 2 \times 10^{13} = 1.2 \times 10^{14} = n_i \times e^{(Fn-Ei)/kT} = (1.5 \times 10^{10})e^{(Fn-Ei)/0.0259}$   
where  $kT = 0.0259$  eV at room temperature.
- Thus the electron quasi- Fermi level position  $Fn - Ei$  is found from
- $Fn - Ei = 0.0259 \ln(8 \times 10^3) = 0.233$  eV
- and  $Fn$  lies 0.233 eV above the intrinsic level.
- By a similar calculation, the hole quasi- Fermi level
- $p = p_0 + \delta p = 2.5 \times 10^6 + 2 \times 10^{13} = 0.2 \times 10^{14} = (1.5 \times 10^{10})e^{(Ei-Fp)/0.0259}$  lies  
 $(Ei-Fp) = 0.186$  eV below  $Ei$

# Steady State Carrier Generation; Quasi-Fermi Levels



- The electron quasi- Fermi level position  $E_n - E_i$  is found 0.233 eV above the intrinsic level.
- The hole quasi- Fermi level lies  $(E_i - E_p) = 0.186$  eV below  $E_i$

# Steady State Carrier Generation; Quasi-Fermi Levels

- The Fermi level  $E_F$  used is meaningful only when no excess carriers are present. However, we can write expressions for the steady state concentrations in the same *form* as the equilibrium expressions by defining separate *quasi-Fermi levels*  $F_n$  and  $F_p$  for electrons and holes. The resulting carrier concentration equations  $n = n_i x e^{(F_n - E_i)/kT}$
- $p = n_i x e^{(E_i - F_p)/kT}$  can be considered as defining relations for the quasi-Fermi-levels.
- In summary the quasi-Fermi levels  $F_n$  and  $F_p$  are the steady state analogues
- of the equilibrium Fermi level  $E_F$ . When excess carriers are present,
- the deviations of  $F_n$  and  $F_p$  from  $E_F$  indicate how far the electron and hole
- populations are from the equilibrium values  $n_0$  and  $p_0$