Lecture 6

Absorption and Photo-generation

Photogeneration

Light with photon energy, hν < Eg is not easily absorbed. A convenient expression for the energy of light is E=1.24/λ where λ is the wavelength of the light in um.

Light with energy, hν > Eg is absorbed with the "unabsorbed" light intensity as a function of depth into the semiconductor is I(x) = $I_o e^{-\alpha x}$

where Io is the initial light intensity, x is distance and α is the absorption coefficient [1/cm].

hν < Eg

hν > Eg

Light (λ,ν)

Semiconductor

0

L

x
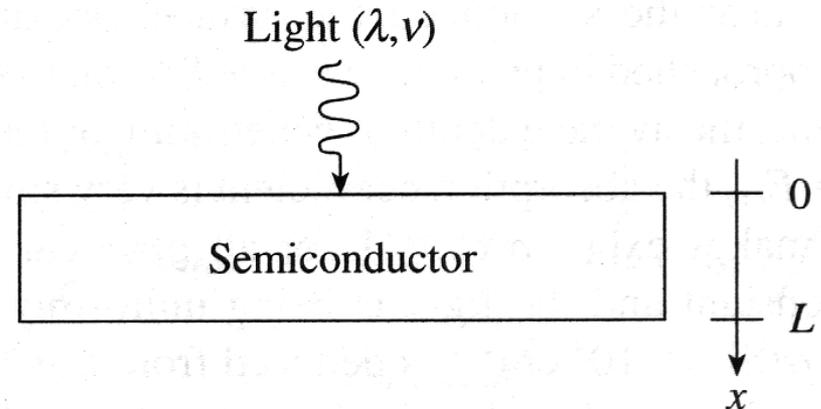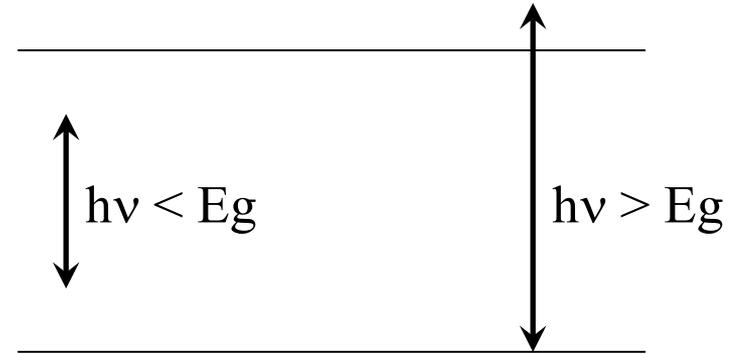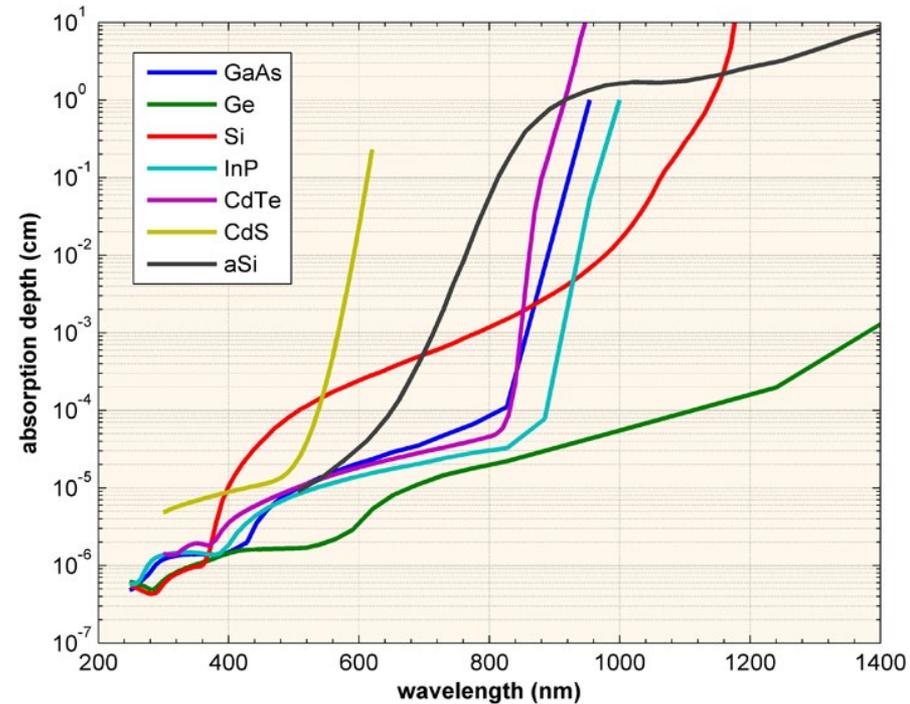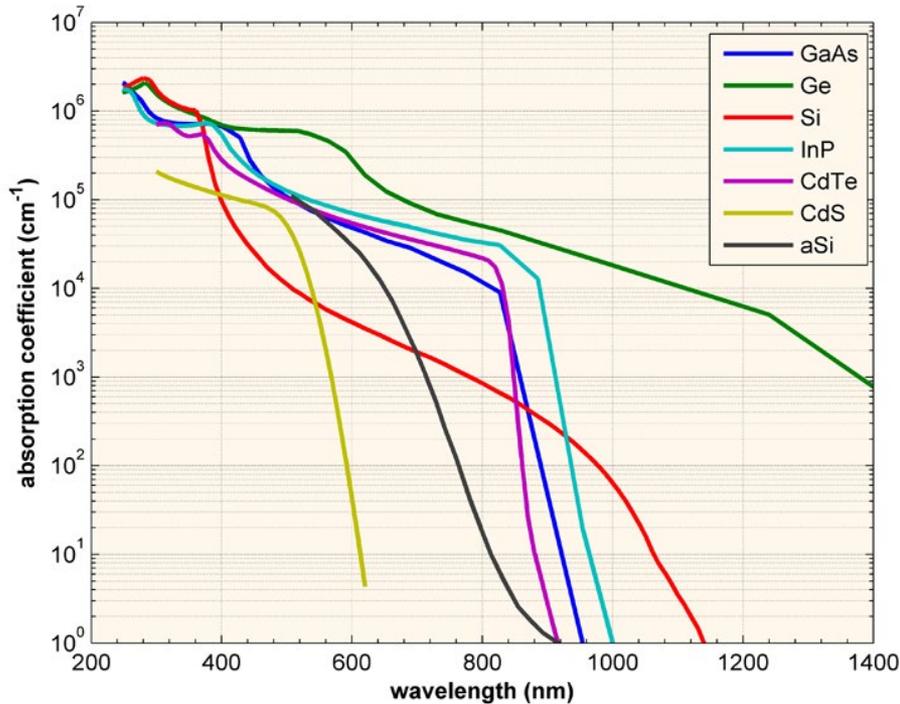
Absorption

The absorption depth is given by the inverse of the absorption coefficient, or α^{-1}. The absorption depth gives the distance into the material at which the light at that wavelength drops to about 36% of its original intensity (by a factor of 1/e).

Absorption

ASTM G173-03 Reference Spectra
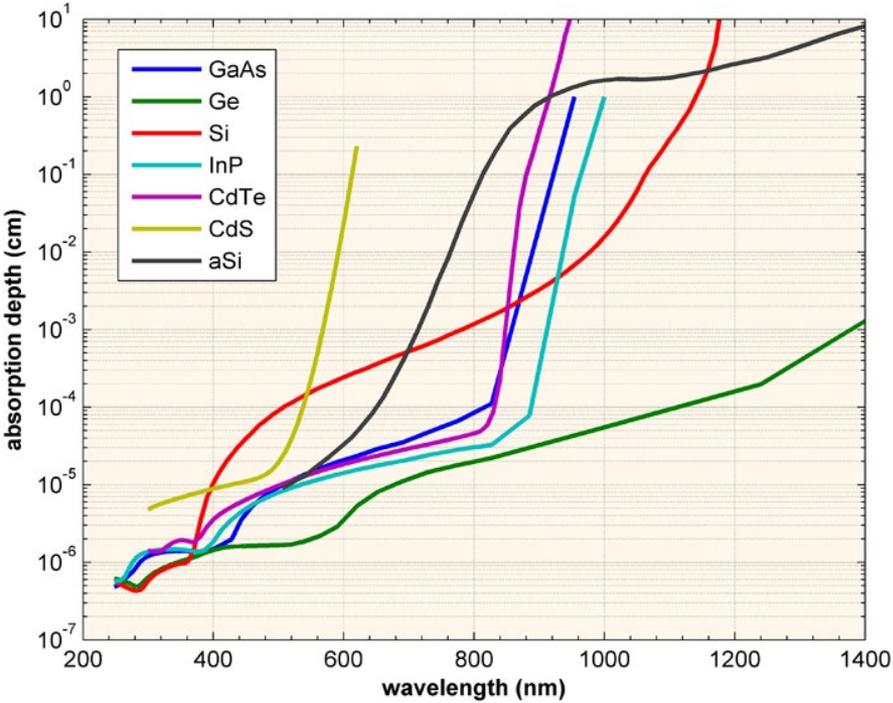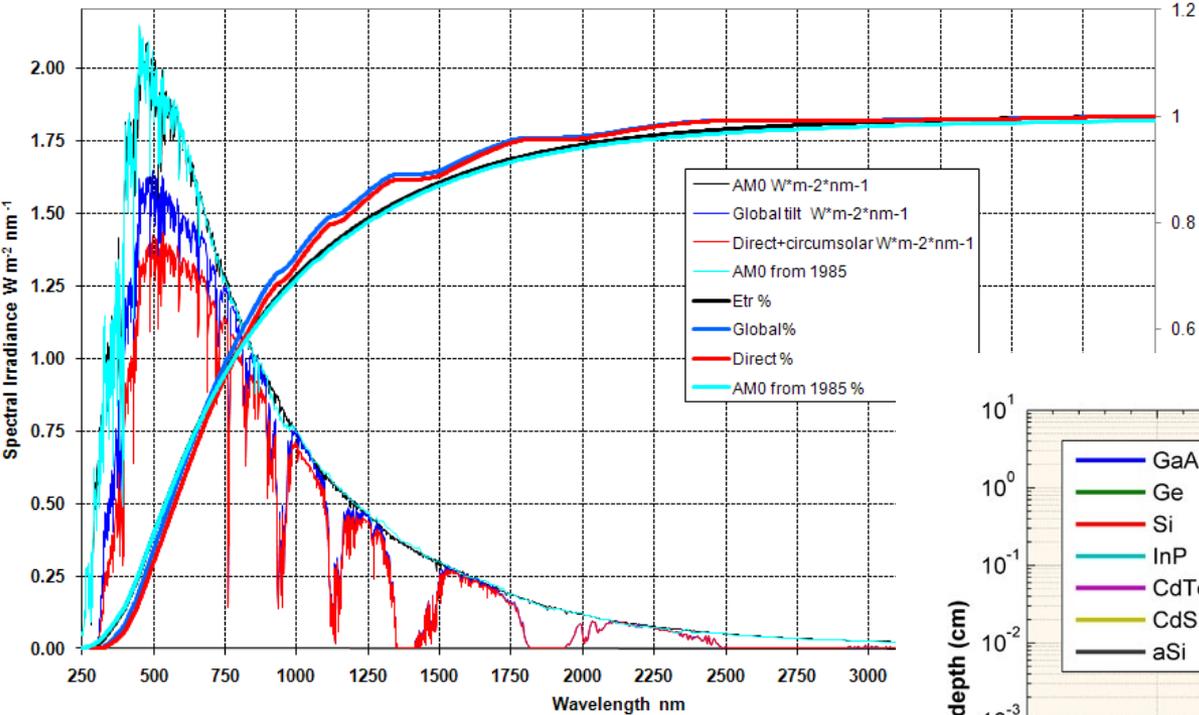
Real Energy band Diagrams:

Direct verses Indirect Bandgaps
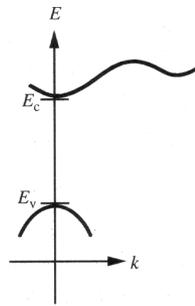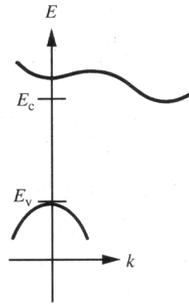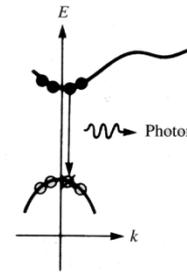
(a) Direct semiconductor   (b) Indirect semiconductor   (a) Direct semiconductor   (b) Indirect semiconductor
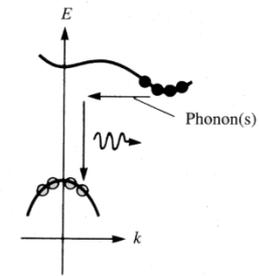
Figure 3.17 General forms of $E-k$ plots for direct and indirect semiconductors.   **Figure 3.18** $E-k$ plot visualizations of recombination in direct and indirect semiconductors.

The energy required to liberate an electron from the atom (the energy bandgap) is the same in all "escape directions" (directions that an electron can leave the atom).

Example: Electrons directed toward a neighboring atom would have a high escape energy, while electrons directed toward a channel in the crystal (a hole through the crystal) would have a lower escape energy.

Thus, the energy band diagram is actually a function of momentum. Additionally, both energy and momentum (directed mass motion) must be conserved during any transition.

Real Energy band Diagrams:

Direct verses Indirect Bandgaps

Direct Bandgap

Indirect Bandgap

Probability of a "direct transition" from valence band to conduction band is high!

Probability of a "direct transition" from valence band to conduction band is low but if the valence electron is on an atom vibrating in a direction (I.e. has momentum) that lowers the energy required, the probability increases!

Conduction band

E

$E_g = 1.4$ eV

p

Valence band

GaAs

(a)

E

Conduction band

$E_g = 1.1$ eV

p

Valence band

Si

(b)

FIGURE 1-12
Energy-band diagram with energy vs. momentum for (a) GaAs (direct) and (b) Si (indirect).

Real Energy band Diagrams:

Direct verses Indirect Bandgap variations in Light Absorption

Electric field resonates (fields are additive) with the atomic dipole and thus is absorbed strongly!

Polar materials like GaAs, InP, GaN etc… tend to be better at absorbing light. No lattice vibration is needed to absorb the light=direct gap.
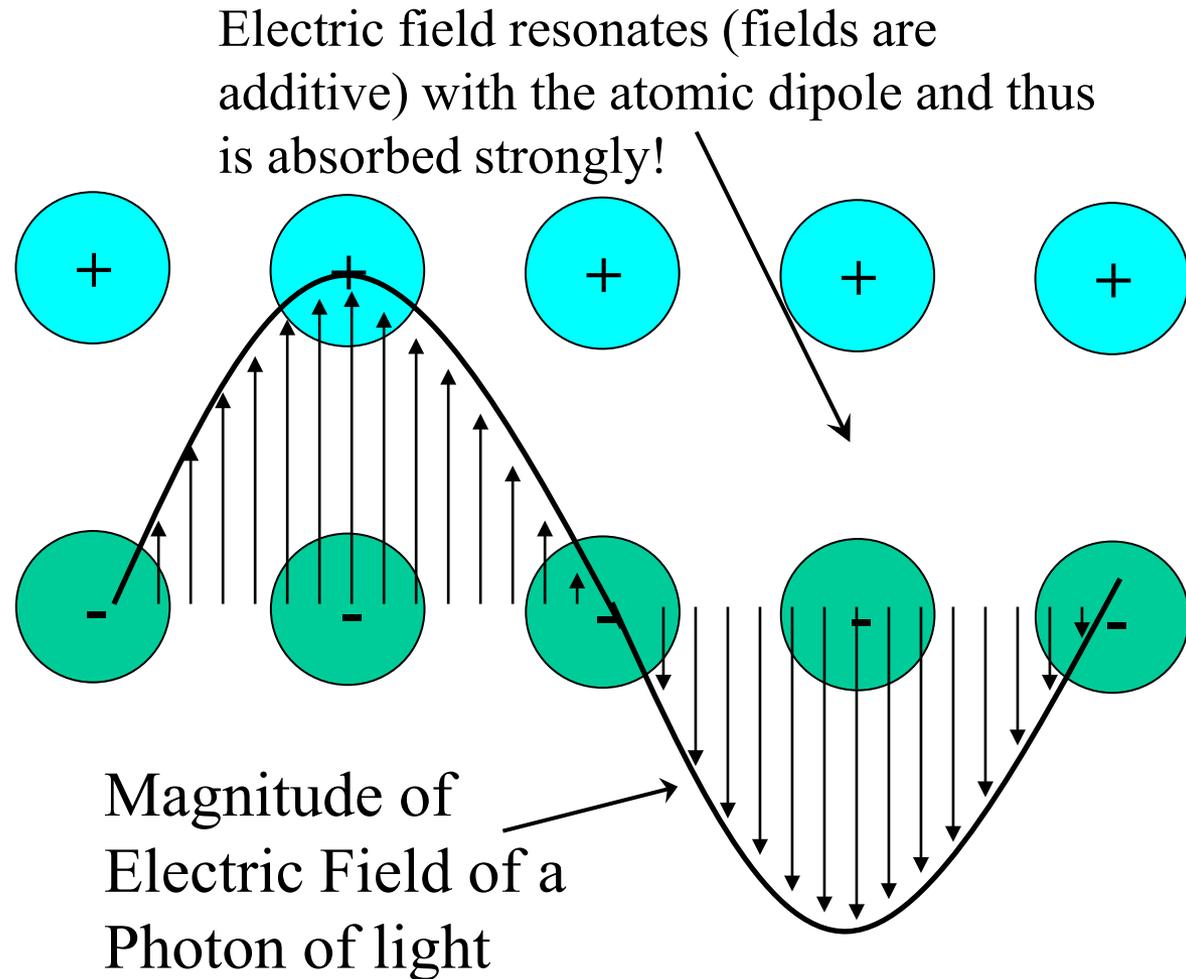
Magnitude of Electric Field of a Photon of light

Real Energy band Diagrams:

Direct verses Indirect Bandgap variations in Light Absorption

After the atoms move apart from their equilibrium positions, the core is displaced from the electron cloud. The photon's electric field then resonates (fields are additive) with the atom core - electron cloud dipole and thus is absorbed.

Covalent materials like Si, Ge etc… tend to be poor light absorbers. A lattice vibration is needed to induce a dipole in the crystal before the light can be absorbed=indirect gap.

0　0　0　+　0

Electron cloud

-

0　0　0　+　0

Magnitude of Electric Field of a Photon of light
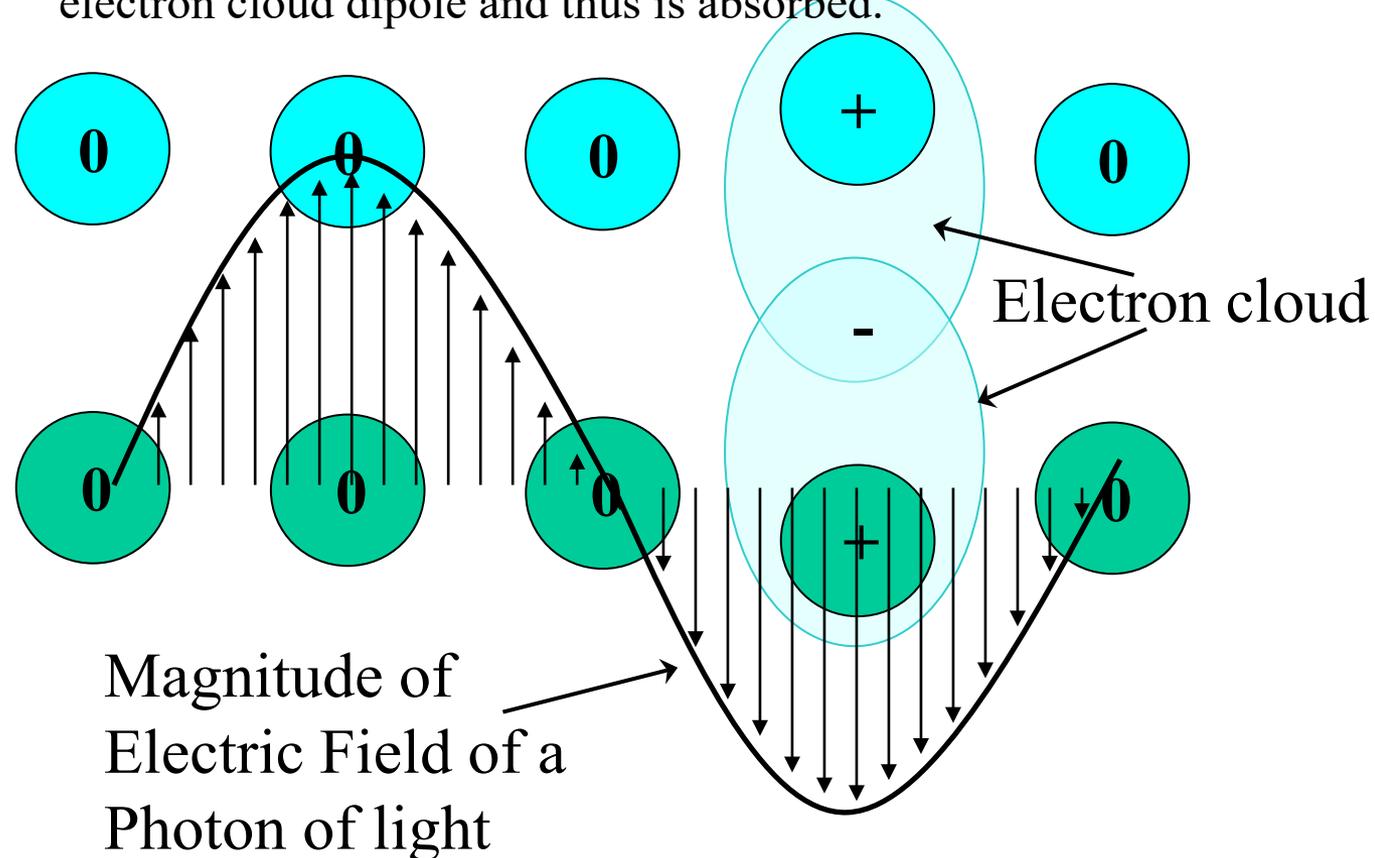
3 Recombination and 3 Generation Mechanisms…
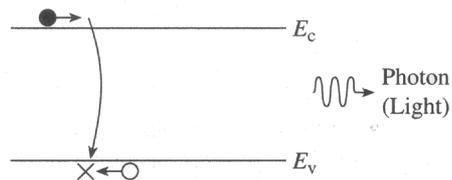
(a) Band-to-band recombination
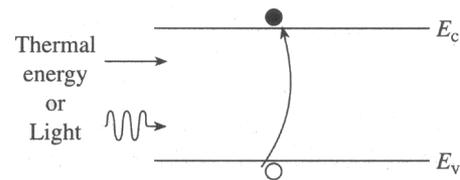
(d) Band-to-band generation
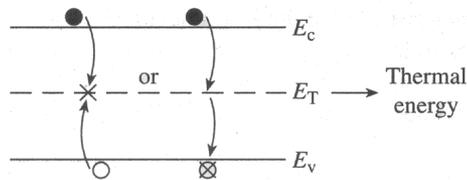
(b) R–G center recombination
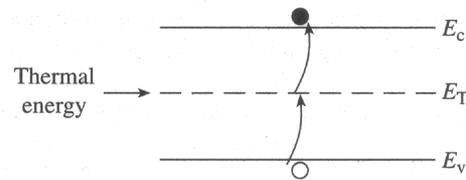
(e) R–G center generation
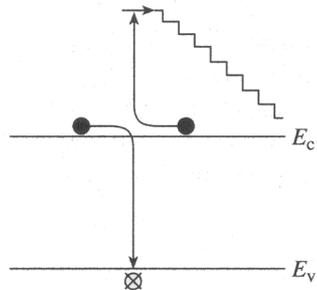
(c) Auger recombination
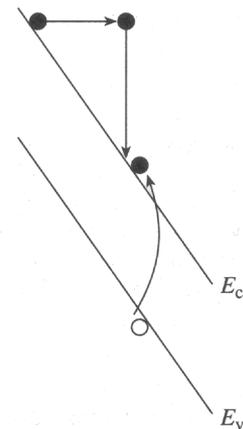
(f) Carrier generation via impact ionization

Figure 3.15 Energy band visualization of recombination and generation processes.

Recombination Mechanisms

E_c
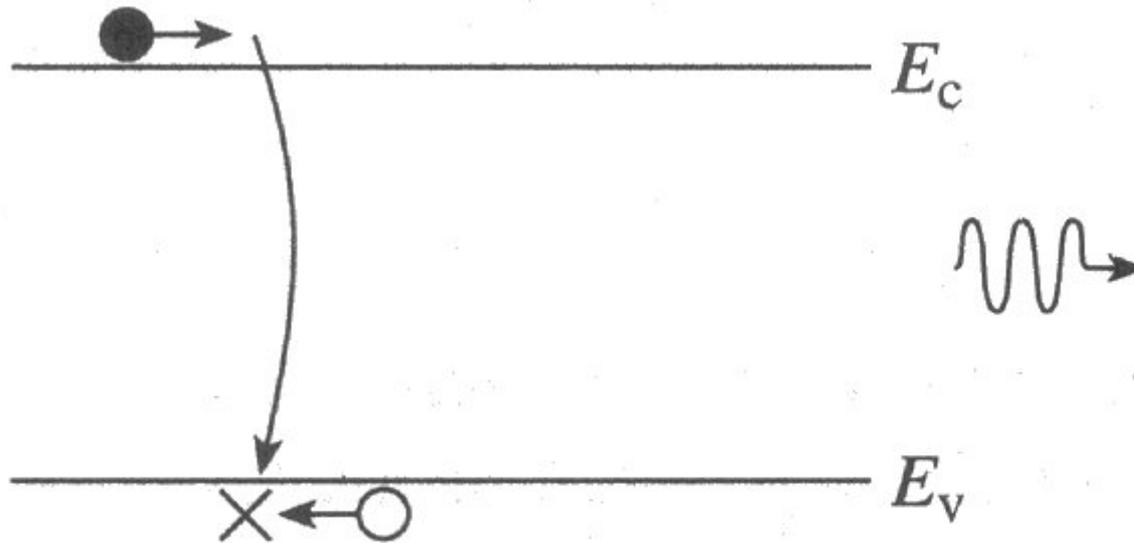
Photon (single particle of light) or multiple phonons (single quantum of lattice vibration - equivalent to saying thermal energy)

E_v

•Band to Band or "direct" (directly across the band) recombination

•Does not have to be a "direct bandgap" material, but is typically very slow in "indirect bandgap" materials.

•Basis for light emission devices such as semiconductor LASERs, LEDs, etc…

Recombination and Generation Mechanisms

"Deep State" Impurities
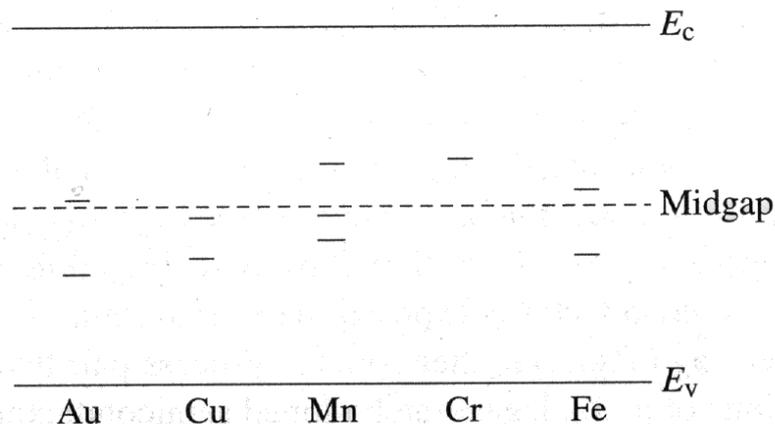
Figure 3.16 Near-midgap energy levels introduced by some common impurities in Si. When an impurity introduces multiple levels, one of the levels tends to dominate in a given semiconductor sample.

Recombination Mechanisms

Energy loss can result in a Photon (single particle of light) but is more often <u>multiple phonons (single quantum of lattice vibration - equivalent to saying thermal energy)</u>

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

• Also known as Shockley-Read-Hall (SRH) recombination.

• Two steps: 1.) 1st carrier is "trapped" (localized) at an unintentional (or intentional) defect/impurity. 2.) 2nd carrier (opposite type) is attracted to the R-G center and annihilates the 1st carrier.

• Useful for creating "fast switching" devices by quickly "killing off" ehp's.

Recombination Mechanisms
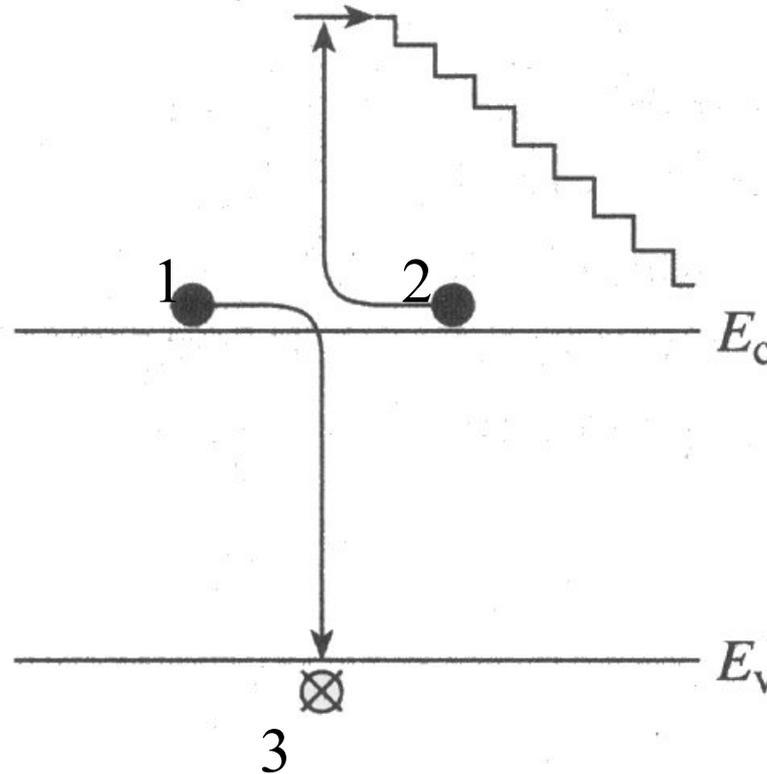
•Auger – "pronounced O-jay" recombination.

•Requires 3 particles.

•Two steps: 1.) 1st carrier and 2nd carrier of same type collide instantly annihilating the electron hole pair (1st and 3rd carrier). The energy lost in the annihilation process is given to the 2nd carrier. 2.) 2nd carrier gives off a series of phonons until it's energy returns to equilibrium energy ($E{\sim}=E_c$) This process is known as thermalization.

Generation Mechanisms
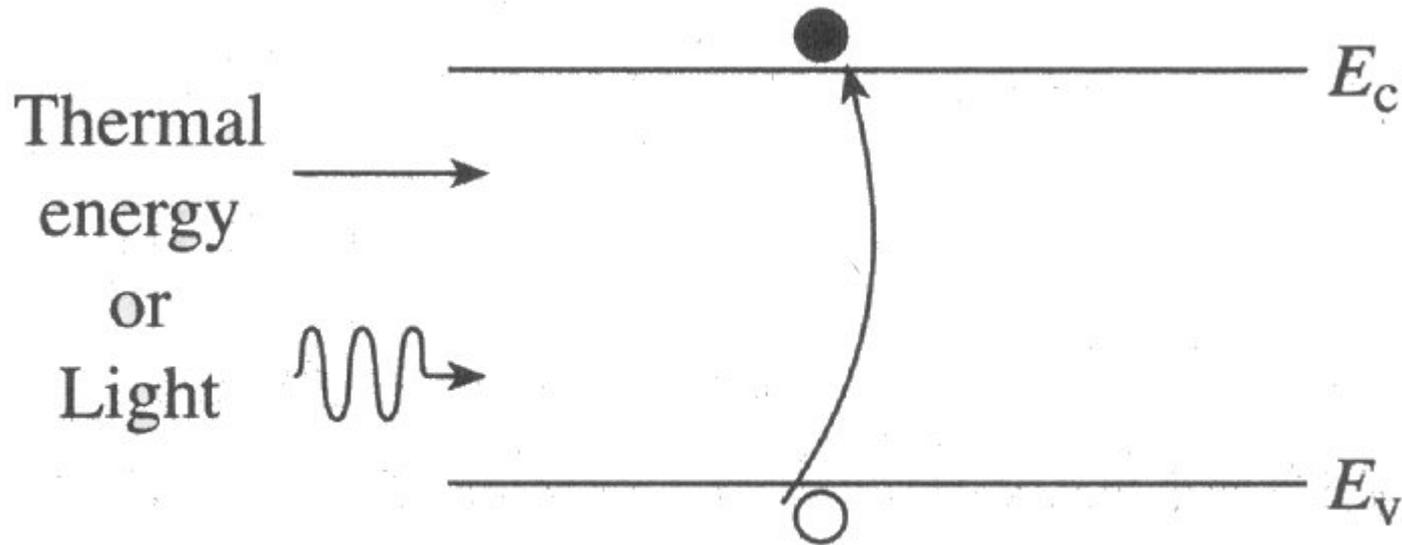
• Band to Band or "direct" (directly across the band) generation

• Does not have to be a "direct bandgap" material.

• Mechanism that results in n_i

• Basis for light absorption devices such as semiconductor photodetectors, solar cells, etc…

Generation Mechanisms
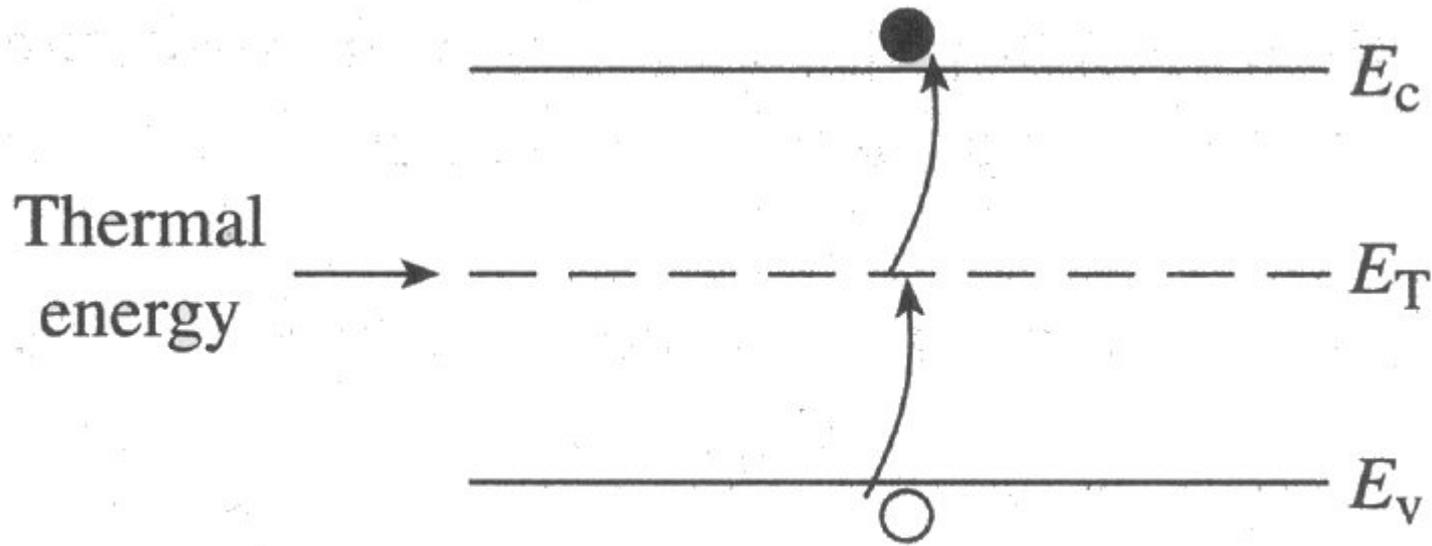
•Recombination-Generation (R-G) Center generation.

•Two steps: 1.) A bonding electron is "trapped" (localized) at an unintentional defect/impurity generating a hole in the valence band. 2.) This trapped electron is then promoted to the conduction band resulting in a new ehp.

•Almost always detrimental to electronic devices. AVOID IF POSSIBLE!

Generation Mechanisms
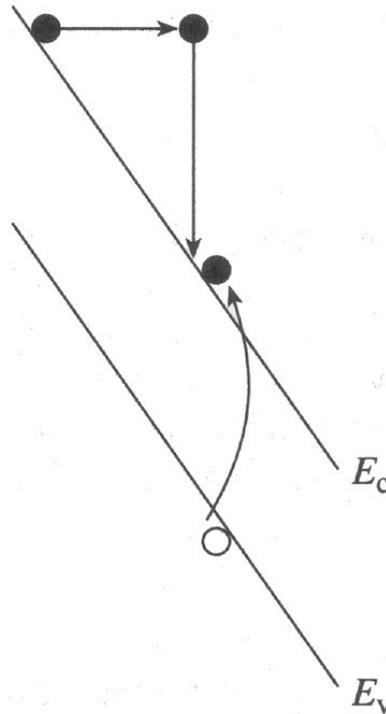
•Impact Ionization generation.

•Requires 3 particles and, typically, high electric fields (steeply bent bands).

•1st carrier is accelerated by high electric fields (or may very rarely gain enough kinetic energy on it's own) and collides with a lattice atom, knocking out a bonding electron creating an ehp.

•If the origin is a high electric field, this process can lead to rapid carrier multiplication known as "avalanching". Can be very useful for very sensitive (but noisy) photodiodes.

•Sets an upper limit on practical electric fields that can be tolerated in many transistors.

Continuity Equation (and subset - Minority Carrier Diffusion Equation)

$$\frac{\partial n}{\partial t} = \left. \frac{\partial n}{\partial t}\right|_{Drift} + \left. \frac{\partial n}{\partial t}\right|_{Diffusion} + \left. \frac{\partial n}{\partial t}\right|_{Re\,combination-Generation} + \left. \frac{\partial n}{\partial t}\right|_{\substack{All\ other\ processes \\ such\ as\ light,\ etc...}}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot J_N + \left. \frac{\partial n}{\partial t}\right|_{Re\,combination-Generation} + \left. \frac{\partial n}{\partial t}\right|_{\substack{All\ other\ processes \\ such\ as\ light,\ etc...}}$$

Low Level Injection Shockley-Read Hall Recombination/Generation

$$\frac{\partial (\Delta n_p)}{\partial t} = D_N \frac{\partial^2 (\Delta n_p)}{\partial x^2} - \frac{(\Delta n_p)}{\tau_n} + G_L$$

Minority Carrier Diffusion Equation

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot J_N + \frac{n_i^2 - np}{\tau_p (n + n_1) + \tau_n (p + p_1)} + \left[G_L(x,\lambda) = G_{LO}e^{-\alpha x} \right]\ldots$$

General Shockley-Read Hall recombination/Generation

$$\ldots + B(np - n_i^2) + C_n n(np - n_i^2) + C_p p(np - n_i^2)$$

Band to Band Recombination /Generation

Auger Recombination/Generation

$$where\ldots n_1 \equiv n_i e^{(E_T - E_i)/kT} \quad and \quad p_1 \equiv n_i e^{(E_i - E_T)/kT}$$

Photogeneration

Each Photon with energy greater than Eg can result in one electron hole pair. Thus, we can say,

$$\left.\frac{\partial n}{\partial t}\right|_{Light} = \left.\frac{\partial p}{\partial t}\right|_{Light} = G_L(x,\lambda) \quad where \ G_L(x,\lambda) = G_{LO}e^{-\alpha x} \quad {}^{\#}\!\!\Big/\!\!\left(cm^3 - Sec\right)$$

If α is small (near bandgap light), the generation profile can be approximately constant.

If α is large (light with energy>> bandgap), the generation profile can be approximated as at the surface.

Important Nomenclature

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.

$\Delta n \equiv n - n_0$ . . . 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.

$\Delta p \equiv p - p_0$

N_T . . . number of R–G centers/cm^3.

$$n = \Delta n + n_o \text{ and } p = \Delta p + p_o$$

In Non-equilibrium, np does not equal n_i^2

Low Level Injection

$\Delta p = \Delta n \ll n_o$ and $n \sim n_o$ in n-type material

$\Delta p = \Delta n \ll p_o$ and $p \sim p_o$ in p-type material

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Carrier Concentrations after a "Perturbation"

Steady State if perturbation has been applied for a long time

Perturbation

$\Delta p(t=0) > p_o$
or
$\Delta p(t=0) < p_o$

$t = 0$

Non-Steady State, Nonequilibrium

$\Delta p(t=0) > \Delta p(t) > p_o$
or
$\Delta p(t=0) < \Delta p(t) < p_o$

$t > 0$

Equilibrium

$\Delta p = 0$

$t \to \infty$

$n \simeq n_0$

E_c
E_F
E_T

E_v

p_0 $\Delta p \ll n_0$
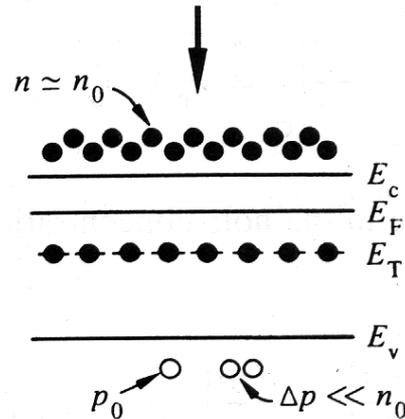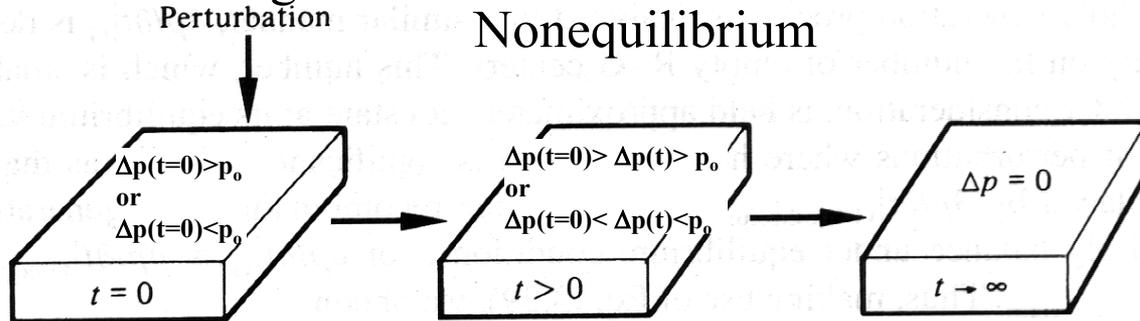
Δp can be $\gg p_o$

If $\Delta p \gg p_o$, $p \sim \Delta p$

After the carrier concentrations are perturbed by some stimulus (leftmost case) and the stimulus is removed (center case) the material relaxes back toward it's equilibrium carrier concentrations.

Material Response to "Non-Equilibrium": Relaxation Concept

Consider a case when the hole concentration in an n-type sample is not in equilibrium, i.e., pn does NOT equal n_i^2

$$\frac{\partial p}{\partial t}\bigg|_{thermal \quad R-G} = -\frac{\Delta p}{\tau_p} \qquad where \quad \tau_p = \frac{1}{c_p N_T}$$

$where \ \tau_p \ is \ the \ \min ority \ carrier \ lifetime$

$c_p \ is \ a \ proportionality \ cons \tan t$

$N_T \ is \ the \ "trap" \ concentration$

- The minority carrier lifetime is the average time a minority carrier can survive in a large ensemble of majority carriers.

- If Δp is negative➔Generation or an increase in carriers with time.

- If Δp is positive➔Recombination or a decrease in carriers with time.

- Either way the system "tries to reach equilibrium"

- The rate of relaxation depends on how far away from equilibrium we are.

Material Response to "Non-Equilibrium": Relaxation Concept

Likewise when the electron concentration in an p-type sample is not in equilibrium, i.e., pn does NOT equal n_i^2

$$\frac{\partial n}{\partial t}\bigg|_{thermal\ R-G} = -\frac{\Delta n}{\tau_n} \qquad where \quad \tau_n = \frac{1}{c_n N_T}$$

$where\ \tau_n\ is\ the\ \min ority\ carrier\ lifetime$

$c_n\ is\ a\ different\ proportionality\ cons\tan t$

$N_T\ is\ the\ "trap"\ concentration$

More generally for any doping or injection case:

$$\frac{\partial n}{\partial t}\bigg|_{thermal\ R-G} = \frac{\partial p}{\partial t}\bigg|_{thermal\ R-G} = \frac{n_i^2 - np}{\tau_p(n + n_1) + \tau_n(p + p_1)}$$

Same unit as above

$where...$

$$n_1 \equiv n_i e^{(E_T - E_i)/kT} \qquad and \qquad p_1 \equiv n_i e^{(E_i - E_T)/kT}$$

Example: After a long time on, a light is switched off

$$\frac{\partial n}{\partial t} = -\frac{\Delta n}{\tau_n} \quad \textit{has a solution}$$

$$n(t) = n_o + \underbrace{\Delta n_o e^{-\left(t/\tau_n\right)}}_{\Delta n(t)} \quad \textit{where } \Delta n_o = \textit{initial excess electron concentration}$$
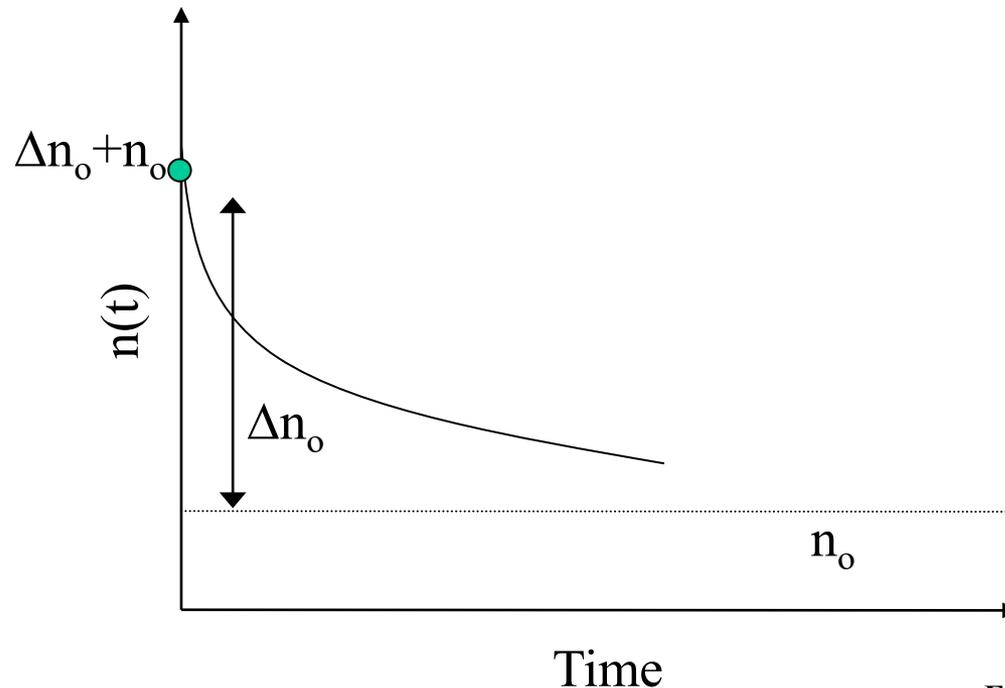
Material Response to "Non-Equilibrium": Relaxation Concept

Carrier Relaxation can also be achieved through Direct recombination

Given: $\Delta n = \Delta p$, $n = n_o + \Delta n$, $p = p_o + \Delta p$

Low Level Injection $\Longrightarrow \Delta n \ll N_a$ and High Level Injection $\Longrightarrow \Delta n \gg N_a$

• Recombination Rate, $R = Bnp$ [#/cm³ sec.] (depends on number of electrons and holes present)

• In Thermal Equilibrium,

$n_o p_o = n_i^2$ where n_i^2 is the n_o-p_o product due to thermal generation (intrinsic generation)

Recombination rate, $R = B \, n_i^2 = G$, Generation Rate where B is a constant

Under Illumination (Non-thermal equilibrium), $np > n_i^2$

Net Recombination Rate, $-dn/dt = R - G = B(np - n_i^2)$

but, $\Delta n = \Delta p$

$$-dn/dt = B(np - n_i^2)$$
$$= B((n_o + \Delta n)(p_o +. \Delta p) - n_i^2)$$
$$= B(n_o p_o - n_i^2 + \Delta p n_o + \Delta n p_o + \Delta n \Delta p)$$
$$= B\Delta n(\; 0 \; + n_o + p_o + \Delta n)$$
$$= B\Delta n(n_o + p_o + \Delta n)$$

Thus, using our lifetime definition,

$$-dn/dt = -\Delta n/ \, \tau_{direct}$$
$$\tau_{direct} = 1/(B(n_o + p_o + \Delta n))$$

Material Response to "Non-Equilibrium": Relaxation Concept

Carrier Relaxation can also be achieved through Direct recombination

Special cases:

Low Level Injection: Δn<<majority carrier density
$$\tau_{direct}=1/(B(n_o + p_o))$$
and if the material is n-type:
$$\tau_{direct}=1/(Bn_o)$$
or p-type:
$$\tau_{direct}=1/(Bp_o)$$

High level injection: Δn>> majority carrier density
$$\tau_{direct}=1/(B\Delta n)$$
Therefore … $-dn/dt = -\Delta n/ \tau_{direct}$
$$-dn/dt = -B(\Delta n)^2$$
Solution of the differential equation no longer yields a simple exponential decay

SRH Electron Capture and Emission
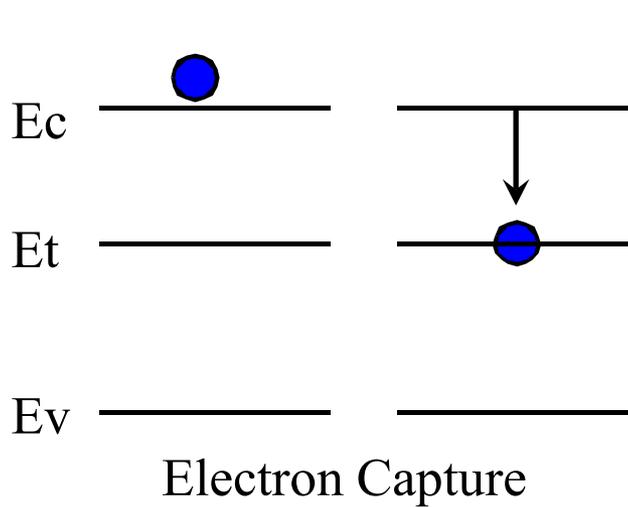
How many electrons are available for capture

Number of empty defect sites

$$c_e = v_{th,e}\ \sigma_n\ n\ N_t\ (1\text{-}f(E))$$

Ec

Et

Ev

Electron Capture

Electron Capture Rate

Capture cross section: Effective size of the defect. Units of area

Thermal velocity: How fast the electrons are moving
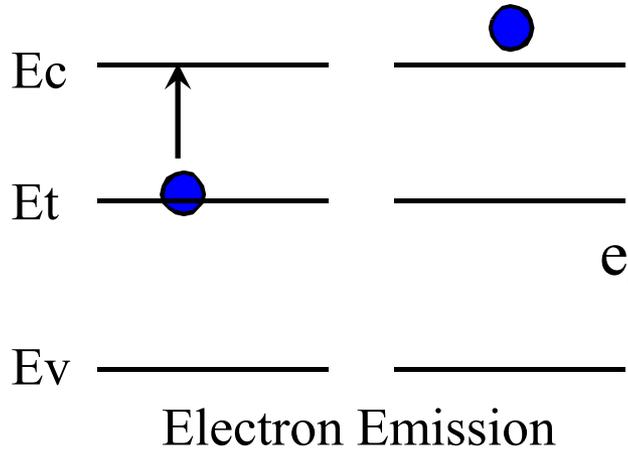
Number of filled defect sites

$$e_e = e_n\ N_t\ f(E)\ \ \text{where } e_n = v_{th,e}\ \sigma_n\ N_c\ e^{-(Ec-Et)/KT}$$

Ec

Et

Ev

Electron Emission

Electron Emission Rate

Hole Capture and Emission

Ec ———————————   ———————————

Et ——————●——————   ——————○——————

Ev ———————————   ———————————
　　　　　○
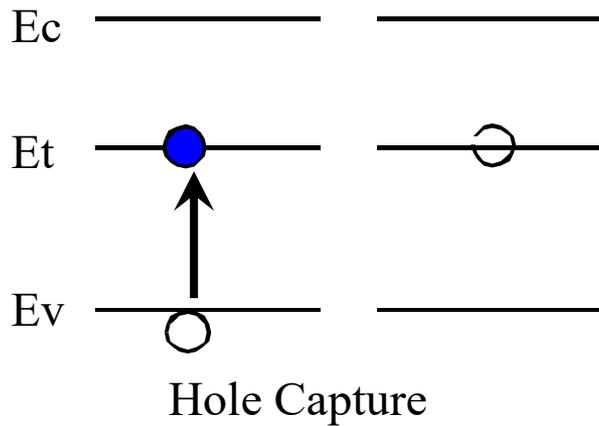
Hole Capture

How many holes are available for capture

Number of filled defect sites

$$c_p = v_{th,p}\ \sigma_p\ p\ N_t\ f(E)$$

Hole Capture Rate

Capture cross section: Effective size of the defect. Units of area

Thermal velocity: How fast the holes are moving

Ec ———————————   ———————————

Et ——————○——————   ——————●——————

Ev ———————————   ———————————
　　　　　　　　　　○
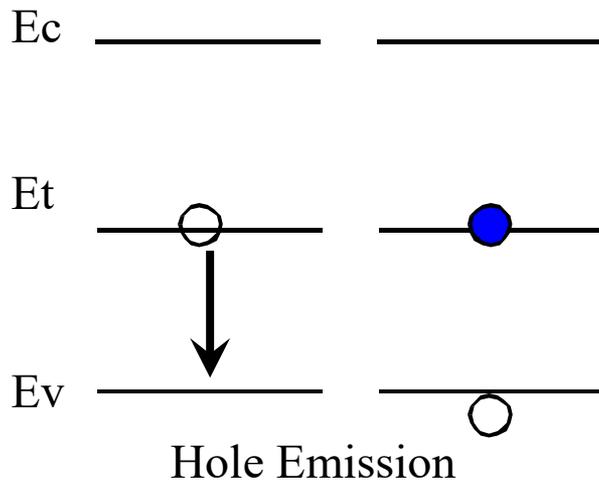
Hole Emission

Number of empty defect sites

$$e_p = e_h\ N_t\ (1 - f(E))$$

Hole Emission Rate

$$\text{where } e_h = v_{th,p}\ \sigma_p\ N_v\ e^{-(E_t - E_v)/KT}$$

Electron and Hole Capture and Emission

Recombination:

      electron capture / hole capture

      hole capture / electron capture

Generation:

      hole emission / electron emission

      electron emission / hole emission

Recycling of carriers into bands:

      hole capture / hole emission

      electron capture / electron emission

Electron and Hole Recombination at Surfaces

Surfaces (or interfaces) are considered "massive planar defects" due to the enormous numbers of broken bonds and thus large numbers of trap states.

Surfaces are characterized by a "Surface recombination velocity" which is the rate at which carriers are flowing toward that surface to recombine. Metals have large/infinite surface recombination velocities (S_e or S_h >1 million cm/Sec) where as well "passivated" surfaces may have S_e or S_h <100 cm/Sec.

Minority Carrier profile under illumination due to high surface recombination velocities

Surfaces

Effect of Surfaces can be averaged with the effect of minority carrier lifetime by:

$$\frac{1}{\tau_{effective}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{Direct}} + \frac{1}{\tau_{Auger}} + \frac{2S}{L}$$