Lecture 8

Equations of State, Equilibrium and Einstein Relationships and Generation/Recombination

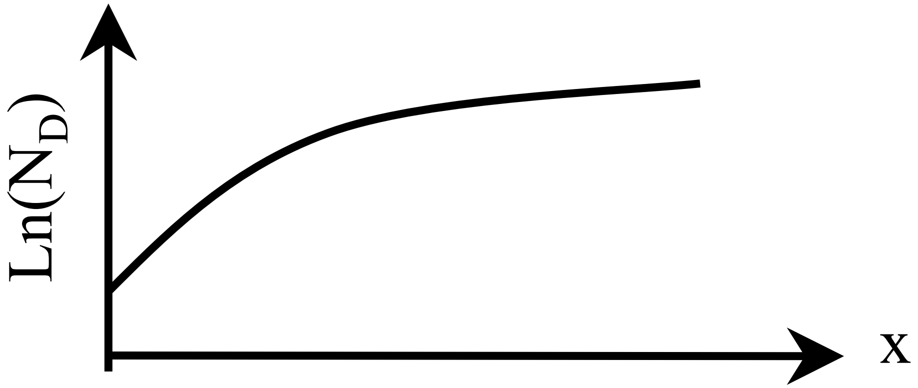
Reading:

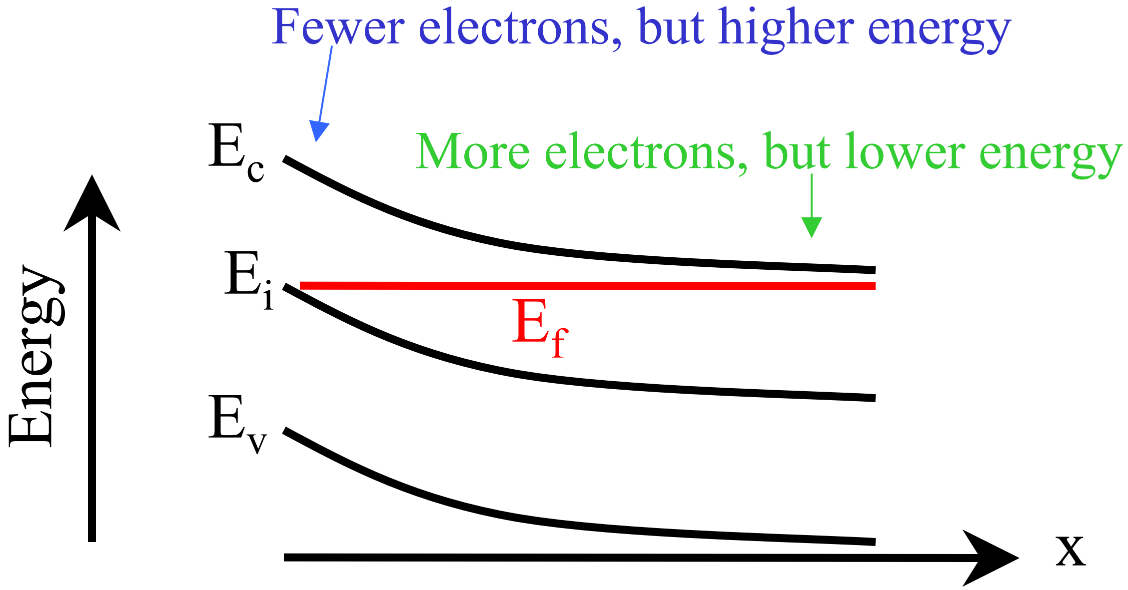
Pierret 3.3-3.4

Equilibrium Concept

Consider a non-uniformly doped semiconductor.

E_c-E_f varies with position



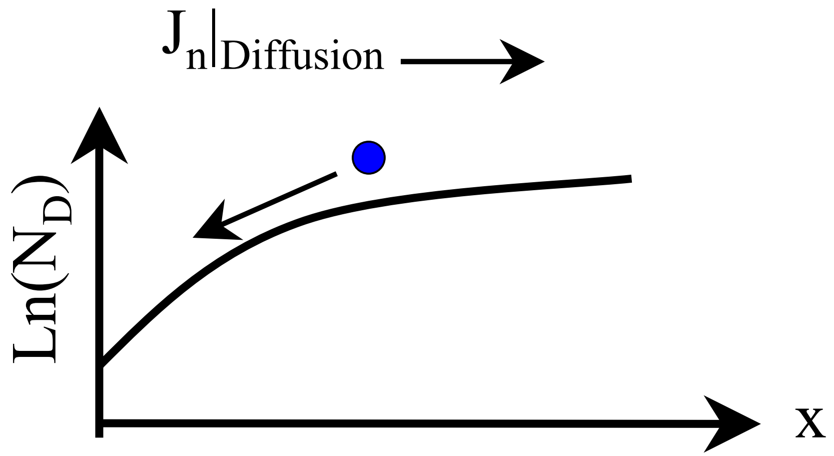


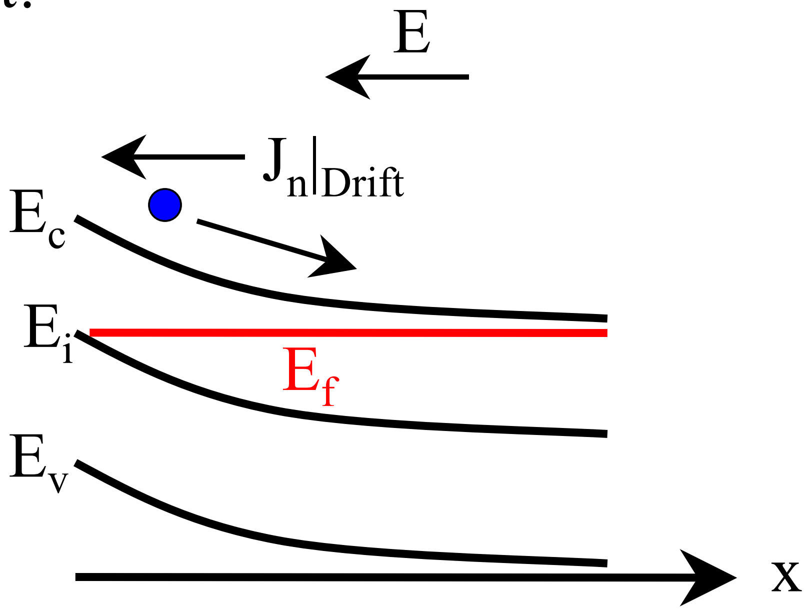
Since the electrons (or holes) are free to move anywhere in the material, the average energy of the electrons can not change. If the average energy did change from one position to another, there would be a net motion of electrons from high energy toward low energy.

E_f must be constant when no current flows!

Equilibrium Concept

- Remember:
  - No net current can flow otherwise we have a “perpetual motion machine”.
  - But dEc/dx is nonzero so we have a drift current component.
  - The drift current component MUST be balanced by a diffusion current component!





Equilibrium Concept

Additionally, since electrons and holes operate “independently of each other”,

$$J_n|_{Diffusion} + J_n|_{Drift} = 0 \quad \text{and} \quad J_p|_{Diffusion} + J_p|_{Drift} = 0$$

- Thus, for non-uniform doping in equilibrium, we have:
  - E_f is constant
  - No net current
  - Carrier Concentration gradients that result in a diffusion current component.
  - A “Built in” electric field that result in a drift current component.
  - BOTH electron and hole components must sum to zero. I.E. $J_n = J_p = 0$

Equilibrium Concept

Consider the case for electrons:

$$J_{n|Drift} + J_{n|Diffusion} = q\mu_n nE + qD_n \frac{dn}{dx} = 0 \qquad (*)$$

$$but \quad E = \frac{1}{q}\frac{dE_i}{dx} \quad and \quad n = n_i e^{(Ef-Ei)/kT} \quad and \quad \frac{dE_f}{dx} = 0$$

Thus, taking the derivative of n,

$$\frac{dn}{dx} = \frac{n_i}{kT} e^{(Ef-Ei)/kT}\left(\frac{dE_f}{dx} - \frac{dE_i}{dx}\right) = \frac{dn}{dx} = -\frac{n_i}{kT} e^{(Ef-Ei)/kT}\left(\frac{dE_i}{dx}\right)$$

$$= -\frac{q}{kT} nE$$

Thus (*) becomes,

$$\mu_n (qnE) - (qnE) D_n \frac{q}{kT} = 0$$

or,

$$\frac{D_n}{\mu_n} = \frac{kT}{q} \qquad Likewise\ for\ holes, \quad \frac{D_p}{\mu_p} = \frac{kT}{q}$$

Einstein Relationship

Equilibrium Concept

Other “need to knows”

kT = Energy (thermal energy)

= $(8.617 \times 10^{-5}$ eV/K) (T in K) [eV]

= $(8.617 \times 10^{-5}$ eV/K) $(1.6 \times 10^{-19}$ J/eV)(T in K) [J]

kT/q = Voltage (thermal voltage)

= J/coulomb

=J/(J/V)=volts

D_n = Diffusion coefficient [cm^2/second]

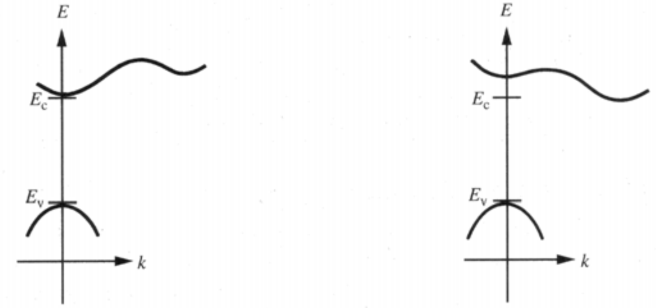
Example:

For Si, $\mu_n \sim 1358$ @ 27 C ====>

D_n = (0.0259 V) (1358 cm^2/V-second) = 35.2 cm^2/Second

Real Energy band Diagrams:

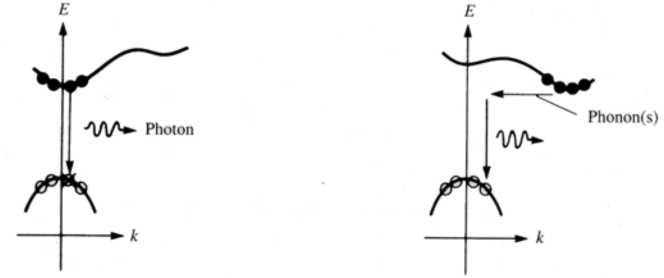
Direct verses Indirect Bandgaps



(a) Direct semiconductor

(b) Indirect semiconductor

Figure 3.17 General forms of E–$\mathbf{k}$ plots for direct and indirect semiconductors.



(a) Direct semiconductor

(b) Indirect semiconductor

Figure 3.18 E–$\mathbf{k}$ 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

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

Direct Bandgap

Indirect Bandgap

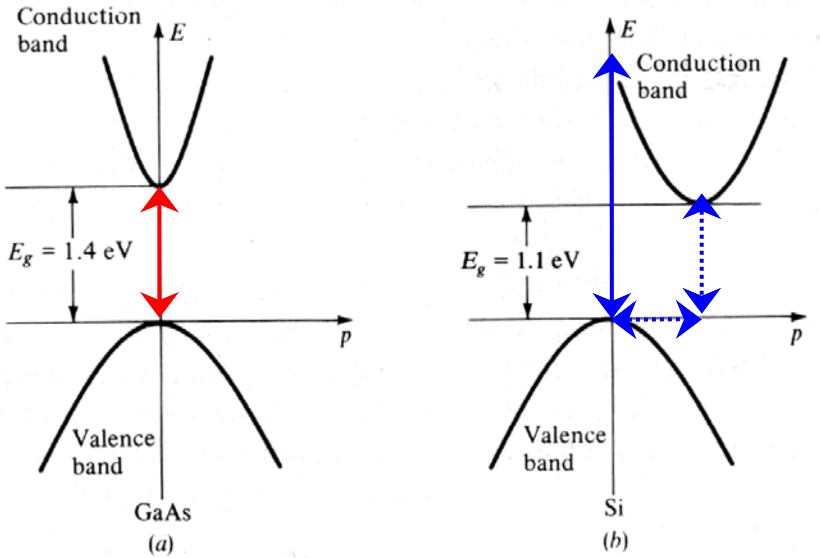


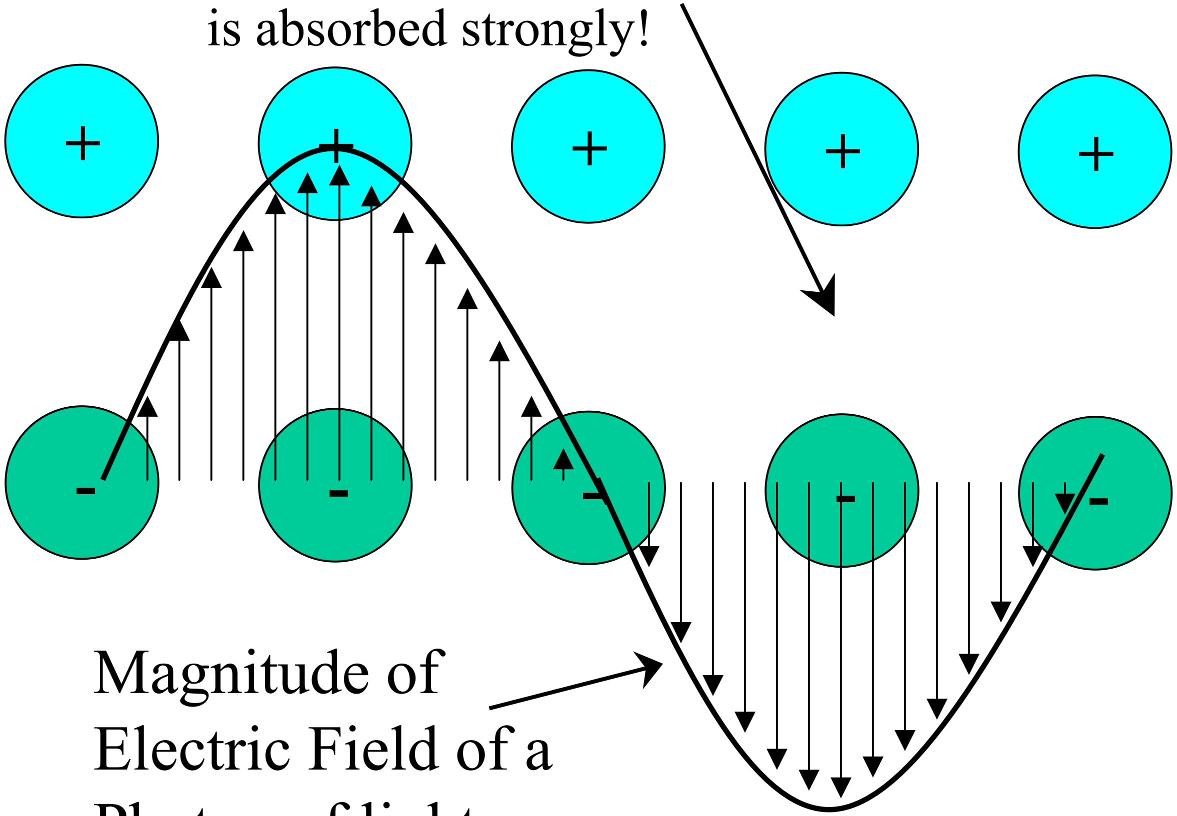
FIGURE 1-12
Energy-band diagram with energy vs. momentum for (*a*) GaAs (direct) and (*b*) Si (indirect).

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!

Real Energy band Diagrams:

Direct verses Indirect Bandgap variations in Light Absorption

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.



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

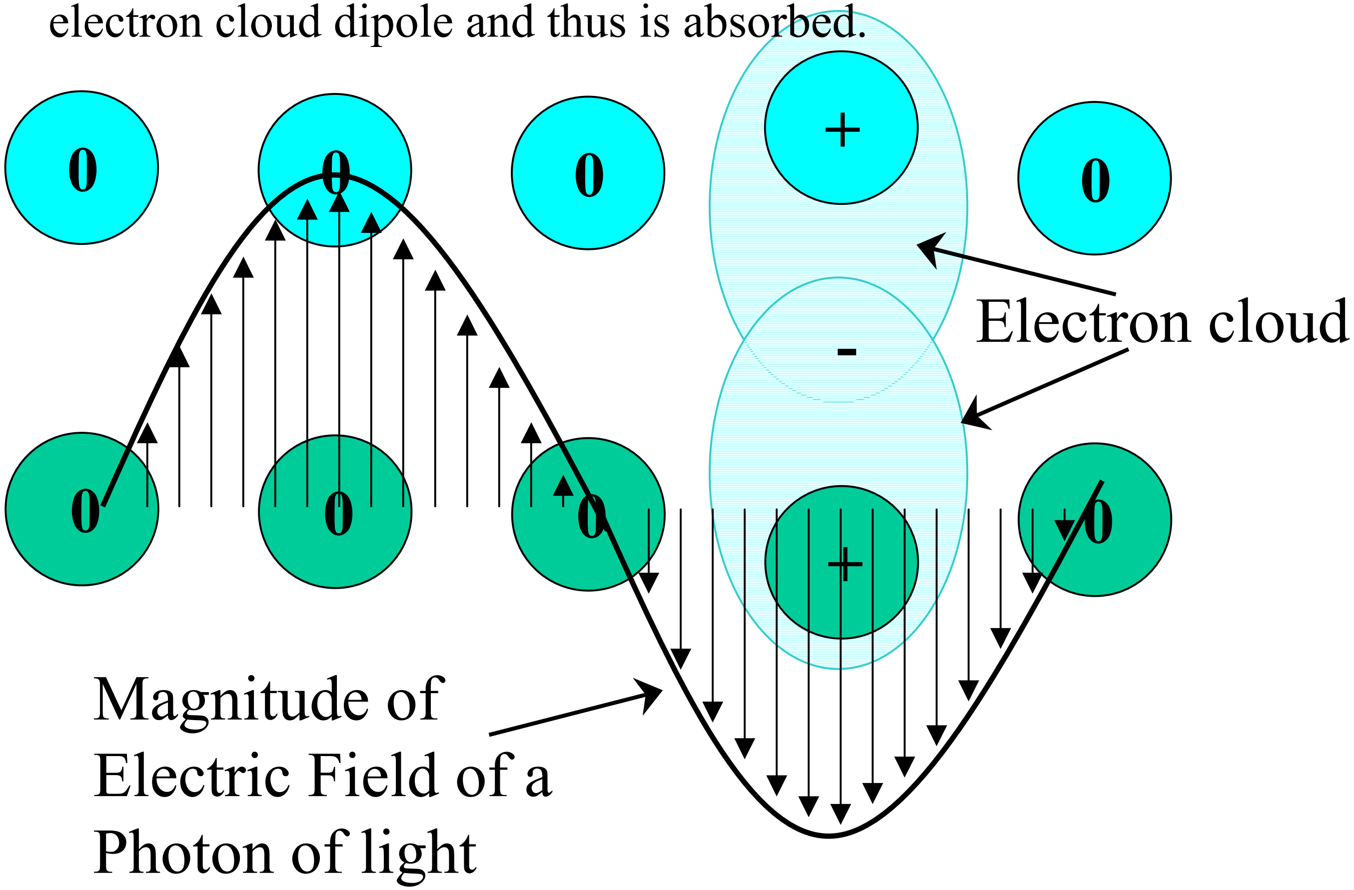
Magnitude of Electric Field of a Photon of light

Real Energy band Diagrams:

Direct verses Indirect Bandgap variations in Light Absorption

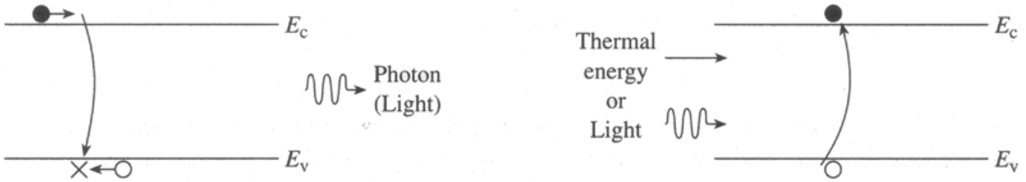
After the atoms move apart from their equilibrium positions, the core is displaced from the electron cloud. The photon's electric field then resonates (fields are additive) with the atom core - electron cloud dipole and thus is absorbed.

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.



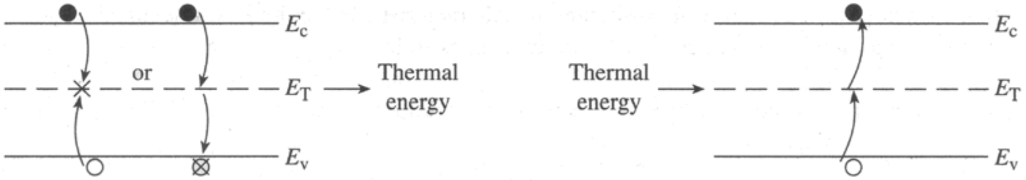
Magnitude of Electric Field of a Photon of light

3 Recombination and 3 Generation Mechanisms…



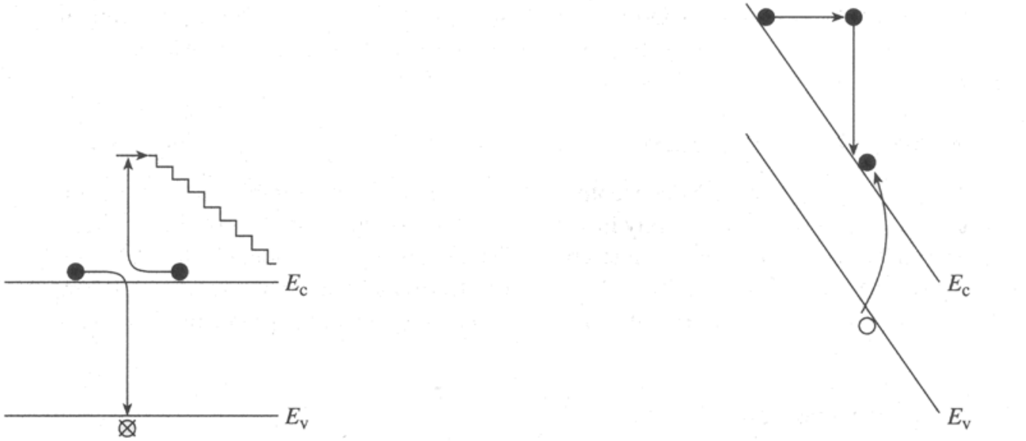
(a) Band-to-band recombination

(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 and Generation Mechanisms

"Deep State" Impurities

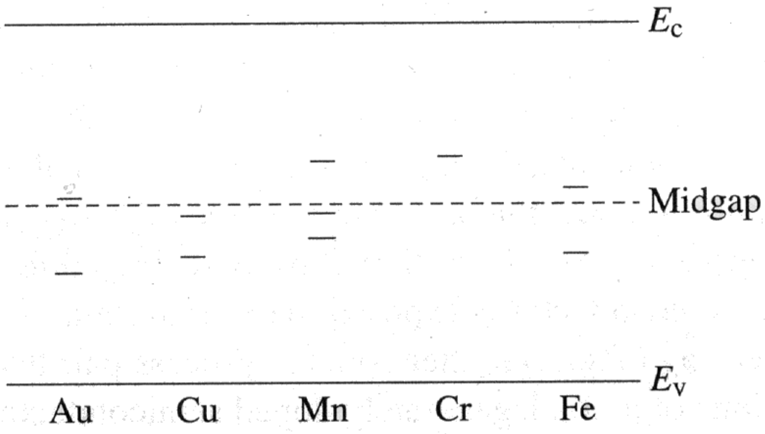
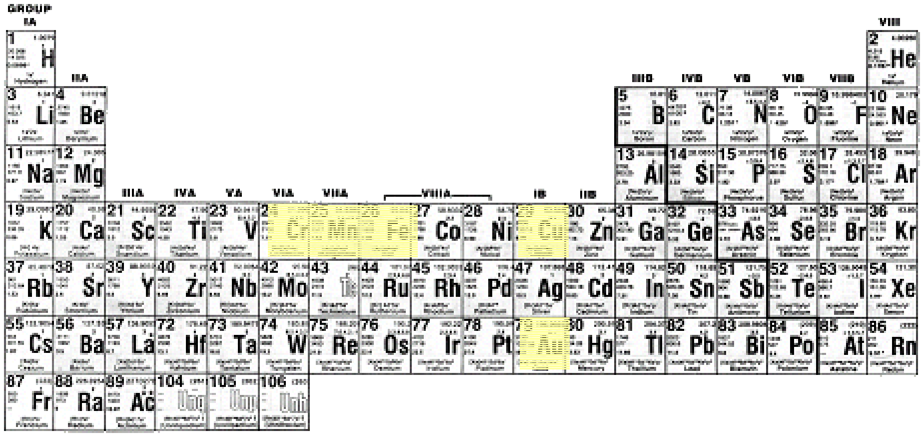


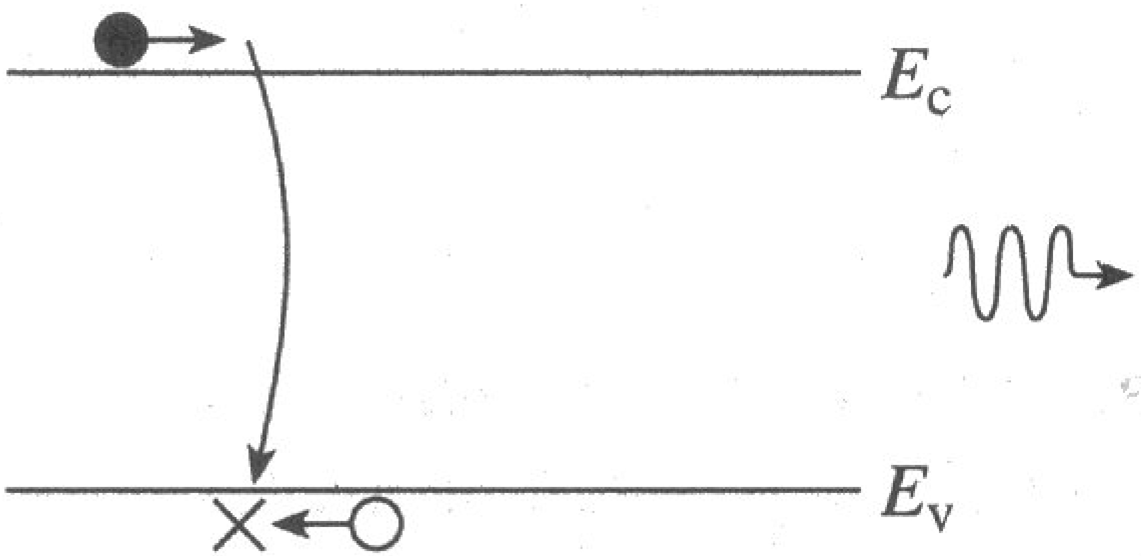
Figure 3.16 Near-midgap energy levels introduced by some common impurities in Si. When an impurity introduces multiple levels, one of the levels tends to dominate in a given semiconductor sample.

PERIODIC TABLE OF THE ELEMENTS



GROUP IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh												

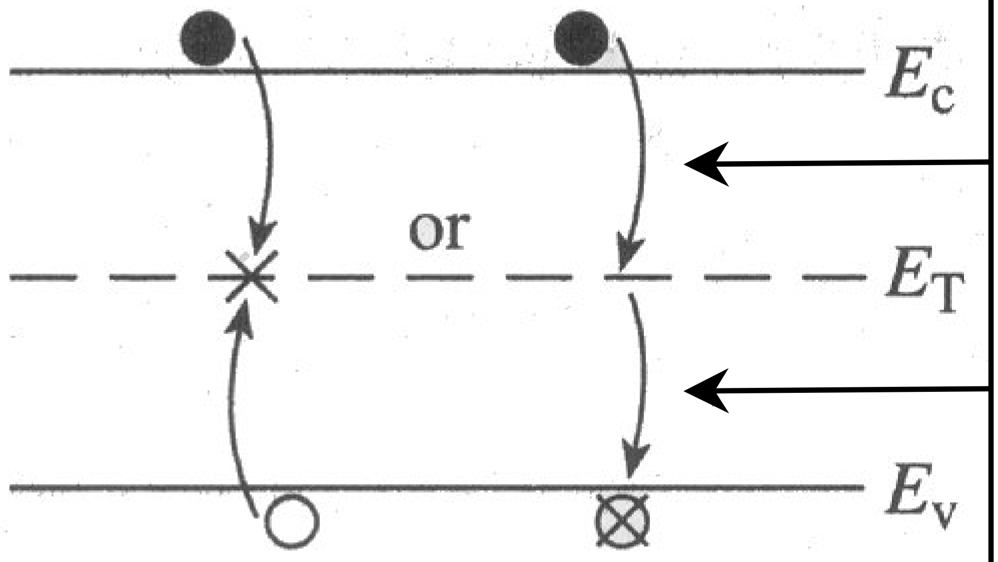
Recombination Mechanisms



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

- 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…

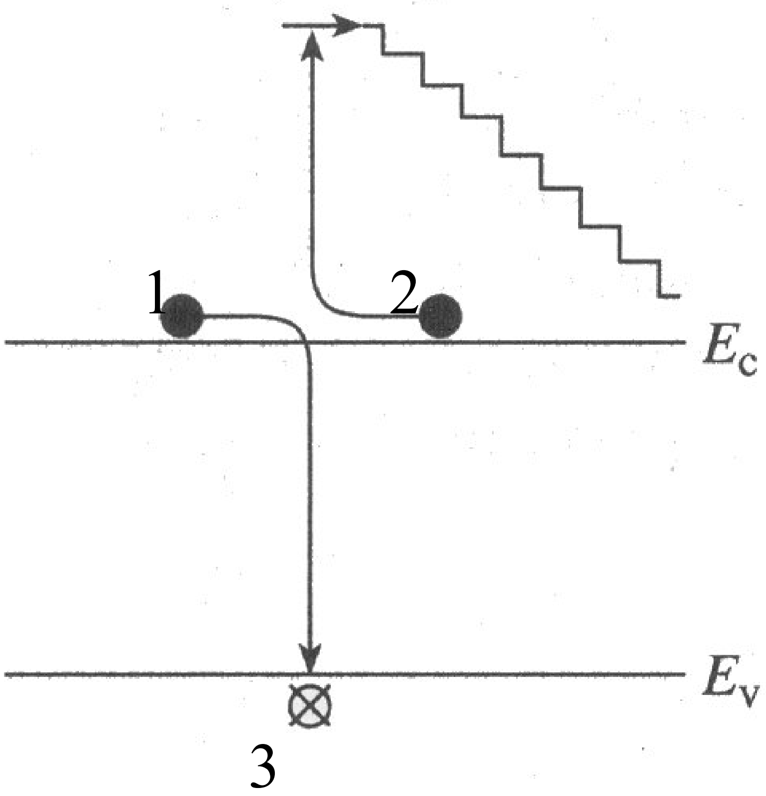
Recombination Mechanisms



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

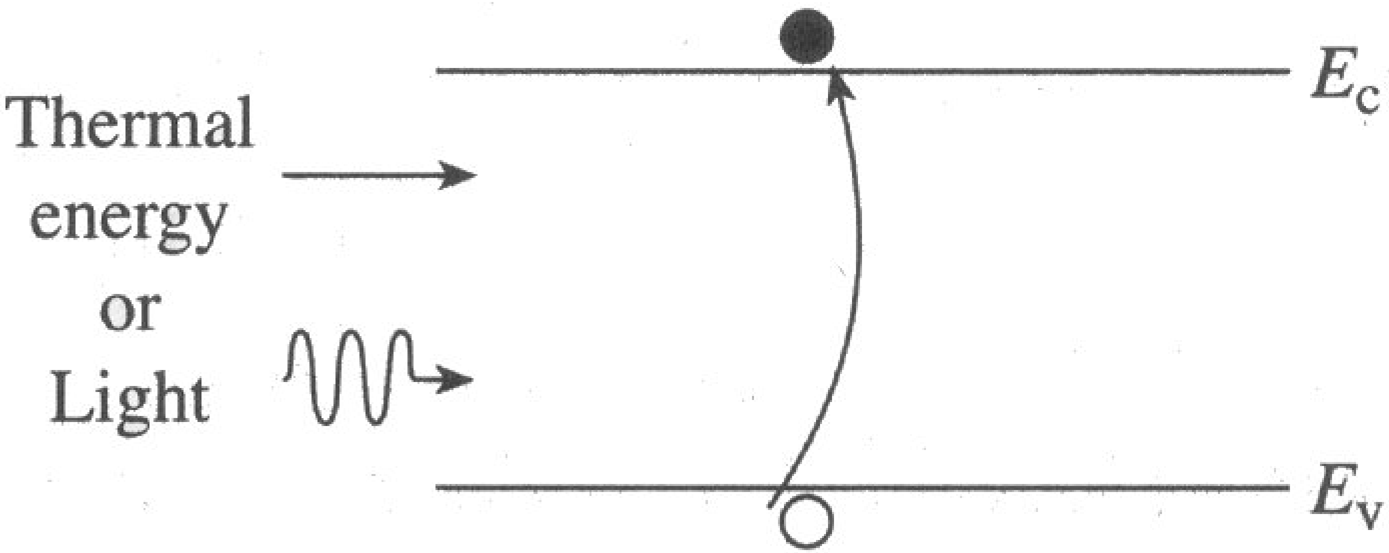
- Recombination-Generation (R-G) Center recombination.
- Also known as Shockley-Read-Hall (SRH) recombination.
- Two steps: 1.) 1st carrier is “trapped” (localized) at an unintentional (or intentional) defect/impurity. 2.) 2nd carrier (opposite type) is attracted to the R-G center and annihilates the 1st carrier.
- Useful for creating “fast switching” devices by quickly “killing off” ehp’s.

Recombination Mechanisms



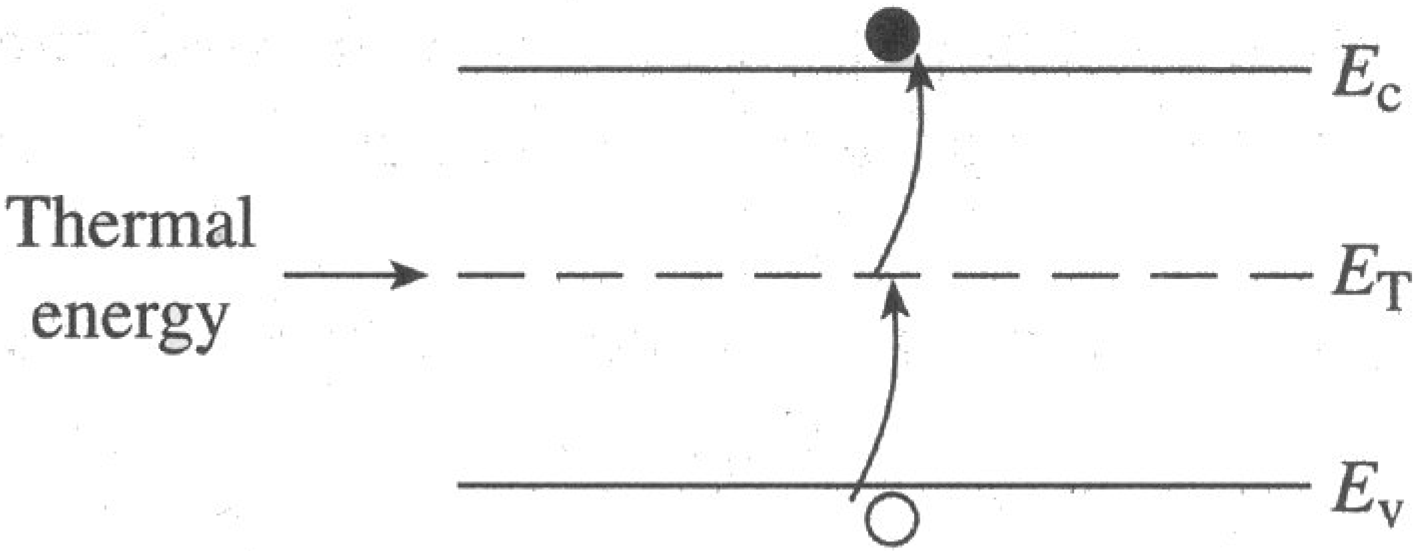
- Auger – “pronounced O-jay” recombination.
- Requires 3 particles.
- Two steps: 1.) 1st carrier and 2nd carrier of same type collide instantly annihilating the electron hole pair (1st and 3rd carrier). The energy lost in the annihilation process is given to the 2nd carrier. 2.) 2nd carrier gives off a series of phonons until it’s energy returns to equilibrium energy ($E \sim= E_c$) This process is known as thermalization.

Generation Mechanisms



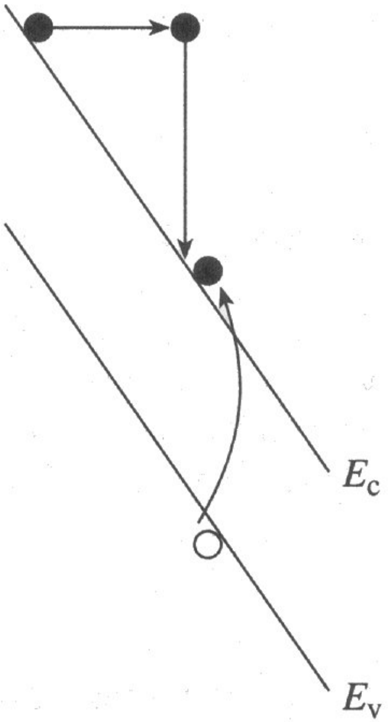
- Band to Band or "direct" (directly across the band) generation
- Does not have to be a "direct bandgap" material.
- Mechanism that results in n_i
- Basis for light absorption devices such as semiconductor photodetectors, solar cells, etc…

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.