Basic Principles of Light Emission in Semiconductors

Class: Integrated Photonic Devices

Time: Fri. 8:00am ~ 11:00am.

Classroom: 資電206

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Model for Light Generation and Absorption

Photon Figures (Particle Nature of Light)

(1) "mass" of photon

$$E = h\nu = mc^2 \longrightarrow m = \frac{h\nu}{c^2} = \frac{h}{c\lambda_0}$$

$$c = \nu\lambda_0$$

(2) Momentum of photon

$p = mc\vec{u}$ $\vec{u}$: unit vector in the direction of travel of the photon

$$\rightarrow p = \frac{h}{\lambda_0}\vec{u} = \hbar\vec{k}$$

Model for Light Generation and Absorption

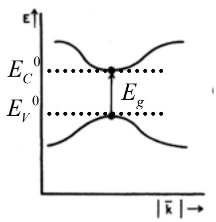
Electron Figures in crystals

(1) "Crystal momentum" of electron is defined as

$p = \hbar k$ where $\hbar = \dfrac{h}{2\pi}$ and $h = 6.624\times 10^{-27}$ (Planck's constant)

k is the wavevector of the electron state and p is not the classic momentum of a free electron mv

(2) "Effective mass" of electron in cystals



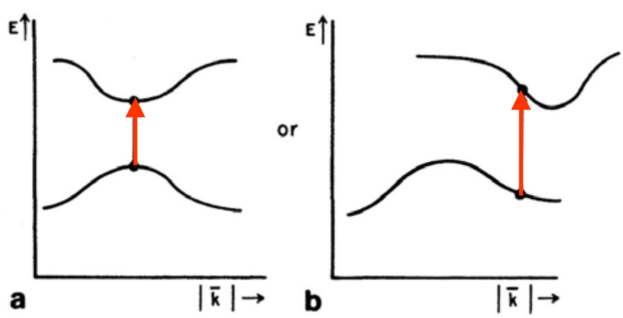
electron $E_{CB} = E_C^{\,0} + \dfrac{\hbar^2 k^2}{2m_e^*}$

hole $E_{VB} = E_V^{\,0} + \dfrac{\hbar^2 k^2}{2m_h^*}$

$\dfrac{1}{m^*} \sim \nabla_k^{\,2} E(k)$

Direct Absorption (Photon-Electron scattering)

Direct Bandgap Material **Indirect Bandgap Material**



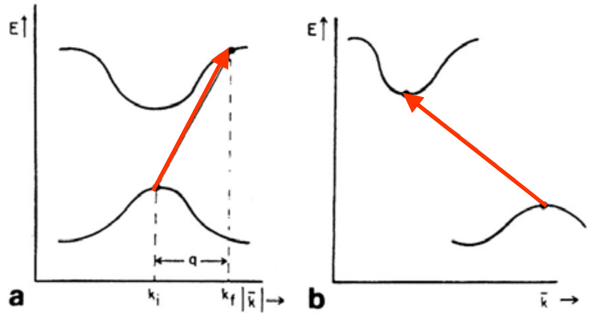
Energy Conservation $E_i + h\nu_{photon} = E_f$

Momentum Conservation $\vec{p}_i + \vec{p}_{photon} = \vec{p}_f$ **or** $\vec{k}_i + \dfrac{2\pi}{\lambda_{photon}}\vec{u} = \vec{k}_f$

$\vec{k}_i \simeq \vec{k}_f$

Indirect Absorption (Photon-Electron-Phonon scattering)

Direct Bandgap Material | **Indirect Bandgap Material**

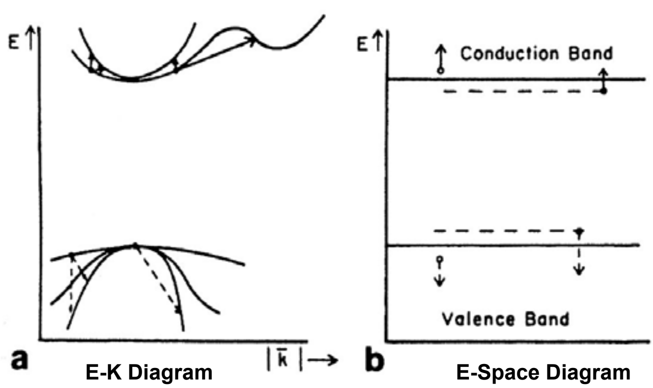


Energy Conservation $E_i + h\nu_{photon} \pm h\omega_{phonon} = E_f$

Momentum Conservation $\vec{k}_i + \frac{2\pi}{\lambda_{photon}}\vec{u} \pm \vec{q} = \vec{k}_f$

Indirect transition rate is much smaller than direct transition rate

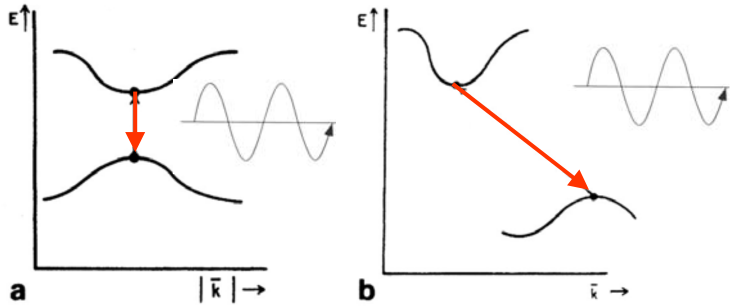
Intraband absorption (Microscopic View)



- **Both direct and indirect transitions also can take place within a band (intraband) or between energy states introduced by dopant atoms and/or defect.**
- **The principles of conservation of energy and momentum apply.**

Light Emission in Semiconductor

Direct Bandgap Material **Indirect Bandgap Material**



Energy Conservation

$$E_i - E_f = h\nu_{photon} \pm h\omega_{phonon}$$

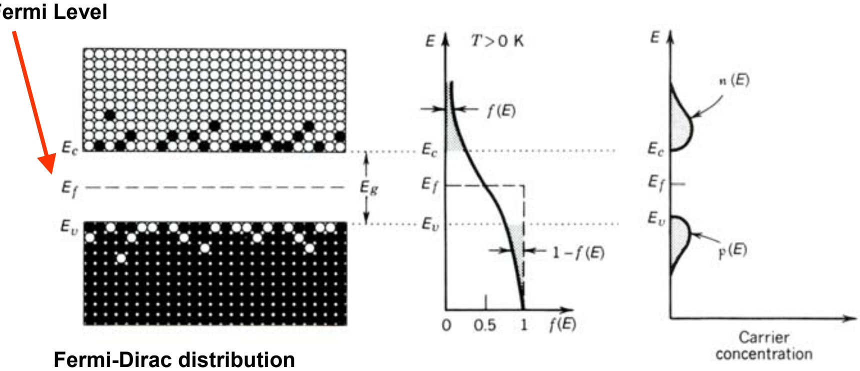
Momentum Conservation

$$\vec{k}_i - \vec{k}_f \pm \vec{q} = \frac{2\pi}{\lambda_{photon}}\vec{u}$$

Under the thermal equilibrium condition, the emitted light is usually re-absorbed

Thermal-Equilibrium Carrier Density

Fermi Level



Fermi-Dirac distribution

$$f(E) = \frac{1}{\exp[(E-E_f)/k_B T]+1}$$

$f(E)$: **probability of occupancy of electron**

$1-f(E)$: **probability of occupancy of hole**

State density of conduction band

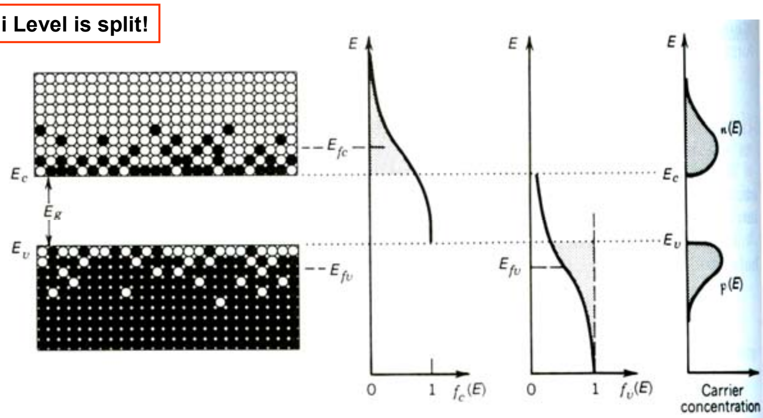
$$n(E) = \sigma_C(E) f(E)$$

$$p(E) = \sigma_V(E)[1-f(E)]$$

State density of valance band

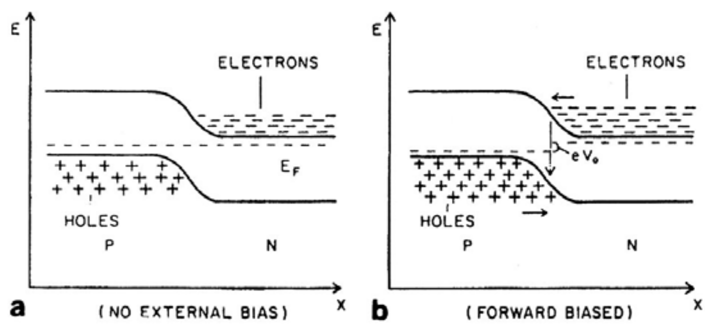
Quasi-Equilibrium Carrier Density

Fermi Level is split!



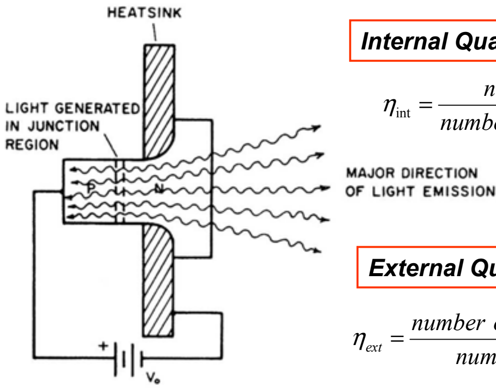
- Fermi level is split due to optical pumping or current injection
- The electron and hole density changes due to the shift of Fermi-Dirac distribution

p-n Junction Light Emitter



- Electrons and holes are injected and recombined when a forward bias voltage V_0 is applied. (Electroluminescence)
- Compared with gaseous sources, semiconductor lighters usually have single emission peak (corresponding to the band edge) and wide spectrum

A p-n junction light-emitting Diode (LED)



Internal Quantum Efficiency

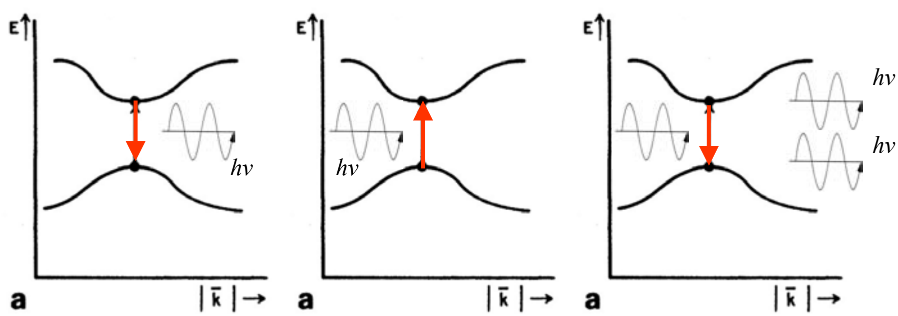
$$\eta_{int} = \frac{number\ of\ photons\ generated}{number\ of\ hole\text{-}electron\ pair\ injected}$$

External Quantum Efficiency

$$\eta_{ext} = \frac{number\ of\ photons\ emitted\ in\ desired\ direction}{number\ of\ hole\text{-}electron\ pair\ injected}$$

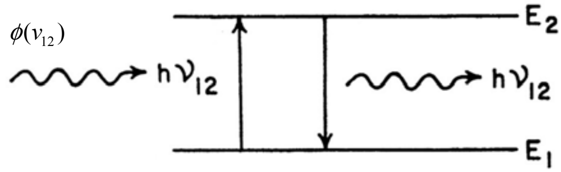
- **Actually, much of light is reabsorbed (due to reflection) before it leaves the diode**
  - **Making the layer of material between the junction and the surface very thin**
  - **Choosing the a material with a very small absorption coefficient**

Interband Light-Matter Interaction



- **Spontaneous emission mostly depends on the temperature, which affects the electron and hole distribution. (Fermi-Dirac distribution)**
- **Stimulated emission relies on the intensity of external photon flux**

Band-to-Band Light Matter Interaction



$B_{12}N_1\phi(\nu_{12})$: (stimulated) absorption

$A_{21}N_2$: spontaneous emission

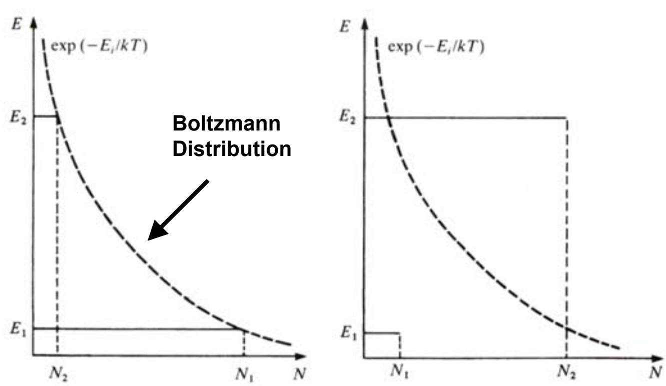
$B_{21}N_2\phi(\nu_{12})$: stimulated emission

$$\frac{stimulated\ emission\ rate}{absorption} = \frac{B_{21}N_2\phi(\nu_{12})}{B_{12}N_1\phi(\nu_{12})} = \frac{B_{21}}{B_{12}}\frac{N_2}{N_1}$$

$$\frac{stimulated\ emission\ rate}{spontaneous\ emission\ rate} = \frac{B_{21}N_2\phi(\nu_{12})}{A_{21}N_2} = \frac{B_{21}}{A_{21}}\phi(\nu_{21})$$

- **N_2 is much smaller than N_1 under thermal-equilibrium condition. Therefore, the stimulated emission is very inefficient**

Population Inversion

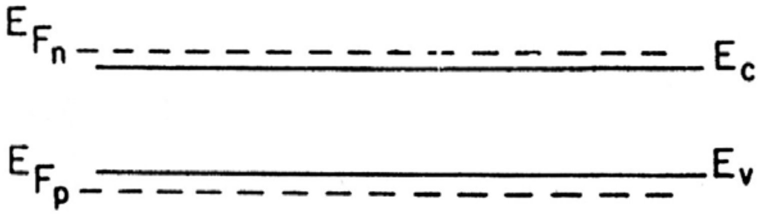


Thermal Equilibrium   After Population Inversion

Boltzmann Distribution: $\frac{N_1}{N_2}\exp[(E_2-E_1)/kT]$

- **Population inversion is essential to let the stimulated emission larger than absorption**

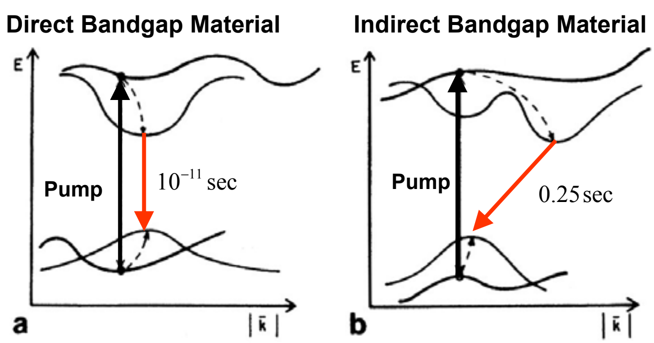
Stimulated Emission



- To get the stimulated emission, N_2 has to be much larger than N1 (population density inversion)

$$E_g \le h\nu \le (E_{Fn} - E_{Fp})$$

Population Density Inversion



- Population density inversion is applicable either by optical pumping or current injection
- The life time of an indirect recombination is long, resulting in nonradiative process such as lattice vibration

Quantum efficiency: ~1(direct bandgap materials) but ~0.001(indirect bandgap materials)