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

\[
E = hv = mc^2 \\
c = \frac{\nu\lambda_0}{c}
\]

\[
m = \frac{hv}{c^2} = \frac{\hbar}{c\lambda_0}
\]

(2) Momentum of photon

\[
p = m\nu = \frac{\hbar \nu}{\lambda_0} : \text{unit vector in the direction of travel of the photon}
\]

\[
p = \frac{\hbar}{\lambda_0} \hat{u} = \hbar \hat{k}
\]
Model for Light Generation and Absorption

Electron Figures in crystals

(1) “Crystal momentum” of electron is defined as

\[ p = \hbar \mathbf{k} \]

where \( \hbar = \frac{\hbar}{2\pi} \) and \( \hbar = 6.624 \times 10^{-27} \) (Planck’s constant)

\( \mathbf{k} \) is the wavevector of the electron state and \( \mathbf{p} \) is not the classic momentum of a free electron \( m \mathbf{v} \)

(2) “Effective mass” of electron in crystals

\[ E_{eB} = E_c^0 + \frac{\hbar^2 k^2}{2m_e^*} \]

\[ \frac{1}{m} - \nabla^2 E(k) \]

\[ E_{eB} = E_c^0 \pm \frac{\hbar^2 k^2}{2m_e^*} \]

Energy Conservation

\[ E_i + h\nu_{\text{photon}} = E_f \]

Momentum Conservation

\[ -p_i + p_{\text{photon}} = p_f \quad \text{or} \quad \mathbf{k}_i + \frac{2\pi}{\lambda_{\text{photon}}} = \mathbf{k}_f \]

Direct Absorption (Photon-Electron scattering)

Direct Bandgap Material

Indirect Bandgap Material
Indirect Absorption (Photon-Electron-Phonon scattering)

Indirect transition rate is much smaller than direct transition rate

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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.

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Light Emission in Semiconductor

Direct Bandgap Material

Indirect Bandgap Material

Energy Conservation

Momentum Conservation

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

Thermal-Equilibrium Carrier Density

Fermi-Dirac distribution

\[ f(E) = \frac{1}{\exp\left(\frac{(E - E_f)}{k_BT}\right) + 1} \]

- \( f(E) \): probability of occupancy of electron
- \( 1 - f(E) \): probability of occupancy of hole

State density of conduction band

\[ n(E) = \sigma_c(E) f(E) \]

\[ p(E) = \sigma_v(E) (1 - f(E)) \]
Quasi-Equilibrium Carrier Density

- 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)

- 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

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

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

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

\[\text{Spontaneous Emission} \quad \text{Stimulated Absorption} \quad \text{Stimulated Emission}\]
Band-to-Band Light Matter Interaction

\[ B_{12}N_1\phi(v_{12}) : \text{(stimulated) absorption} \]
\[ A_{12}N_2 : \text{spontaneous emission} \]
\[ B_{21}N_2\phi(v_{12}) : \text{stimulated emission} \]

\[
\frac{\text{stimulated emission rate}}{\text{absorption}} = \frac{B_{12}N_1\phi(v_{12})}{B_{21}N_2\phi(v_{12})} = \frac{N_1}{N_2}
\]
\[
\frac{\text{stimulated emission rate}}{\text{spontaneous emission rate}} = \frac{B_{12}N_1\phi(v_{12})}{A_{12}N_2} = \frac{N_1}{N_2}
\]

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

Population Inversion

Boltzmann Distribution

Thermal Equilibrium

\[ \frac{N_i}{N_f} \exp\left[\frac{(E_i - E_f)}{kT}\right] \]

After Population Inversion

- Population inversion is essential to let the stimulated emission larger than absorption.
Stimulated Emission

\[ E_{F_n} \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow E_c \]
\[ E_{F_p} \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow E_v \]

- To get the stimulated emission, \( N_2 \) has to be much larger than \( N_1 \) (population density inversion)

\[ E_g \leq h\nu \leq (E_{F_n} - E_{F_p}) \]

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)