Structure, Material and process

1. LED structure

**Epitaxial LED**

**Diffusion LED**

Band diagram

\[
E_F - E_i = -\frac{kT}{q} \ln \left( \frac{n_i}{N_D} \right) \quad E_i - E_F = \frac{kT}{q} \ln \left( \frac{n_i}{N_A} \right)
\]

\[
V_0 = \frac{kT}{q} \ln \left( \frac{N_A N_D}{n_i^2} \right)
\]
\[ N_n = N_{n0} + \Delta n_N \]

\[ \Delta p_N = N_{p0} \left( \frac{e^{V}}{e^{kT}} - 1 \right) \]

\[ \Delta n_p = n_{p0} \left( \frac{e^{V}}{e^{kT}} - 1 \right) \]

\[ p_{n0} \]

\[ P_{n0} \]

\[ \Delta p_p = \Delta n_p \]

\[ \Delta p_p = \Delta n_p \]

\[ J_n = \frac{qD_n}{L_n} \frac{n_i^2}{N_A} \left( e^{\frac{qV}{kT}} - 1 \right) \]

\[ J_p = \frac{qD_p}{L_p} \frac{n_i^2}{N_D} \left( e^{\frac{qV}{kT}} - 1 \right) \]

\[ J_r = \left( \frac{qn_iW}{2\tau_n} + \frac{qn_iW}{2\tau_p} \right) \left( e^{\frac{V}{\eta kT}} - 1 \right) \]
FIGURE 3.25  Free space wavelength coverage by different LED materials from the visible spectrum to the infrared including wavelengths used in optical communications. Hatched region and dashed lines are indirect $E_g$ materials.
Band Gap versus Lattice Parameter for IV, III-V, and II-VI Semiconductors
2. **LED Materials**

- **II–V ternary alloys**: GaAs$_{1-y}$P$_y$, $y > 0.45$
  - Indirect
- GaAs$_{0.55}$P$_{0.45} \rightarrow$ 630 nm, red bandgap
- Ga As $\rightarrow$ 870 nm, Infrared
- N doped GaAs$_{1-y}$P$_y$ $\leftrightarrow$ indirect bandgap
  - N forms electron traps, which attract holes in its vicinity and eventually recombined gives light
  - Nitrogen doped GaAs$_{1-y}$P$_y$ is widely used in green, yellow, & orange LED

3. **Blue LED**

- SiC
  - Indirect bandgap $E_g \sim 2.86$ eV
  - Luminous efficiency $\eta \sim 0.04$ lm/W, $D_{ext} = 0.02\%$
  - Research to find good iso-electronic trap to increase $\eta$
- **II-IV** compounds
  - ZnSe/ ZnS:SE, material system Not Mature
    - Issues: a) No Lattice-Matched Substrate
    - b) Degradation.

- GaN ← best one
  - Two historical problems solved by Nichia Corp
    1. GaN is usually n-type as grown (probably N vacancy)
    1st n-type GaN was doped with Mg and annealed
      in a N₂ atmosphere ⇒ p-type GaN
      Now, Zn has also been used
    2. No Lattice-Matched substrates
      - use Sapphire (Al₂O₃), but lattice match is poor.
      - lattice mismatch ~ 15%
    ⇒ Breakthrough: Polycrystalline GaN buffer.
      - Luminous Intensity ~ 1 cd
      - P_{out} = 1500 μW, \ θ_{ext} = 2.7%
      - \lambda = 450 nm, \ \Delta \lambda = 70 nm.
**SiC substrates**

- Better lattice match to GaN
- Better thermal conductivity
- Better thermal expansion match.

However, high substrate cost, ~$2000 each

Sapphire ~$200 each.

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**White LED**

Place blue LED chip inside phosphor-coated package

4-emission spectrum

\[ \lambda \sim 10 \text{ lumens/W} \]
2. Emission Spectra

- Electron & hole peaks
  - at $\frac{1}{2} k_BT + E_C$
  - at $-\frac{1}{2} k_BT + E_V$
- Width $\sim 2k_BT$

$p$ - $P$ = \frac{C}{n}$

- $(\hbar \nu)_\text{peak} = E_g + k_BT$
- $\Delta h\nu = 2k_BT$

$\lambda = \frac{C}{\nu n}$

$\Delta \lambda = \frac{C}{\nu^2 n} \Delta \nu = -\frac{\lambda_0^2}{hc/n} \Delta(\hbar \nu)$

$= -\frac{\lambda_0^2}{hc/n} - 2k_BT$
\[ \Delta \lambda \propto \lambda^2 \]

\[
\frac{\Delta \lambda_{\text{InGaAs}} \left( \sim \lambda \sim 1.3 \text{mm} \right)}{\Delta \lambda_{\text{GaAs}} \left( \lambda \sim 0.85 \text{ mm} \right)} = 2.3
\]

a). GaAs \( \lambda_0 \sim 0.85 \text{ mm} \), \( \Delta \lambda = 300 \text{ Å} = 30 \text{ nm} \)

b). InGaAsP \( \lambda_0 \sim 1.08 \text{ mm} \), \( \Delta \lambda \approx 500 \text{ Å} \)

c). InGaAsP, \( \lambda \sim 1.3 \text{ mm} \), \( \Delta \lambda \approx 700 \text{ Å} \)

- \( \Delta \lambda \) increases with \( N_a \)

- \( \Delta \lambda \) increases as injection level increase
Examples:

1. LED output wavelength variations

Consider GaAs LED, $E_g = 1.42 \text{eV} @ 300 \text{K}$.

\[
\frac{dE_g}{dT} = -4.5 \times 10^{-4} \text{ eV/K}, \quad \text{find } \frac{d\lambda}{dT}.
\]

\[(h\nu)_{\text{peak}} = E_g + k_B T \Rightarrow \frac{h}{\lambda} = \frac{E_g}{k_B T} + k_B T\]

\[
\Rightarrow \quad \frac{hc}{n(E_g + k_B T)} = \lambda \quad \Rightarrow \quad \frac{d\lambda}{dT} = \frac{h}{n} \cdot \frac{dE_g/dT}{(E_g + k_B T)^2}
\]

\[
= 2.8 \times 10^{-10} \text{m/K} \approx 0.8 \text{ nm/K}
\]

2. The ternary alloy \(\text{In}_{1-x}\text{Ga}_x\text{As}_{y}\text{P}_{1-y}\)

To avoid lattice mismatch, \(y = 0.2x\).

\[E_g = 1.35 - 0.72y + 0.12y^2, \quad 0.5x \leq 0.47\]

Calculate the composition of InGaAsP to make the emission peak at 1.3 \mu m.

\[(h\nu)_{\text{peak}} = E_g + k_B T \Rightarrow \frac{hc}{\lambda} = E_g + k_B T\]

\[
\lambda = 1.3 \mu m
\]

\[
\Rightarrow \quad E_g = 0.928 \text{ eV} = 1.35 - 0.72y + 0.12y^2
\]

\[
\Rightarrow \quad y = 0.66 \quad \Rightarrow \quad x = \frac{y}{2y} = 0.3
\]

\[\text{In}_{0.7}\text{Ga}_{0.3}\text{As}_{0.66}\text{P}_{0.34}\]
3. **Bandwidth** (modulation bandwidth)
   - wide bandwidth ⇒ require shorter carrier lifetime
   - \( I(\omega) = \frac{I_{dc}}{\sqrt{1+(\omega t)^2}} \quad P \propto I^2(\omega) \)
   - \( P_{3dB} = \frac{P_{dc}}{2} \quad \omega t = 1, \quad f_{3dB} = \frac{1}{\pi \omega} \)
   - ⇒ short \( T_{car} \)
   - \( \frac{1}{\omega} = \frac{1}{\omega_r} + \frac{1}{\omega R} \)
   - \( T_r = \frac{1}{N_a B_r} \) at low injection
   - \( f_{3dB} = \frac{B_r N_a}{2\pi} \), independent of current at low injection.

4. High injection:
   - \( T_r = \frac{1}{B_r \Delta N_p} \)
   - \( J = \frac{q V_{an}}{C} \) ⇒ \( \Delta N = J T / 2W \)
   - \( \Rightarrow \frac{1}{\omega} = \frac{1}{\omega_r} \left( \frac{B_r J}{q W} \right)^2 \)
   - \( \Rightarrow f_{3dB} = \frac{1}{2\pi} \left( \frac{B_r J}{q W} \right)^2 \)

4. **Bandwidth** ← output power trade off
   a) at low injection:
   - \( f_{3dB} = \frac{B_r N_a}{2\pi} \)
   - \( N_a \uparrow \Rightarrow f_{3dB} \uparrow \)
   - however, heavy doping (> 10^18 cm^-3) forms nonradiative recombination centers, \( T_{car} \downarrow \)
   - e.g. \( N_a \sim 2 \times 10^9 \text{cm}^{-3} \) \( T_r = 1 \text{ns}, \ T_{car} \approx 1 \text{ns} \)
   - \( \eta = \frac{1}{1+\frac{T_r}{T_{car}}} = 50\% \)
b) At high injection
\[ f_{3B} = \frac{1}{2\pi} \left( \frac{Br}{2\nu} \right)^{1/2} \]
reduce \( W \), can increase \( f_{3B} \)
but increase interface recombination

E.g. \( GaAs \)
\[ \tau_r = 10 \text{ ns}, \quad S = 300 \text{ cm/s}, \quad W = 2 \mu m \]
\[ \tau_{tr} = \frac{W}{2S} \approx 200 \text{ ns} \]
\[ \Rightarrow \tau = 9.5 \text{ ns} \Rightarrow f_{3B} = 37 \text{ MHz}, \quad Q_i \approx 100\% \]

if \( W = 0.1 \mu m \)
\[ \tau_{tr} = 10 \text{ ns}, \quad \tau = 5 \text{ ns}, \quad f_{3dB} = 200 \text{ MHz} \]
\[ Q_i = 50\% \]

5. Applications of communication LED

a) Surface emitters
   - large volume, low-cost arrays
   - on wafer testing
   - chip-to-chip optical interconnects

b) Edge emitters
   - short distance fiber optic communication

hw: 3.5, 3.7, 3.8
1. Radiative combination $\rightarrow$ Emit light

2. Non-radiative combination $\rightarrow$ Emit heat

On P side:

$$n_p = n_{p0} + \Delta n_p$$ ← Minority carriers

$$p_p = p_{p0} + \Delta p_p$$ ← Majority carriers

$$\frac{\partial n_p}{\partial t} = -Bn_p p_p + G_{\text{thermal}}$$

$$= -B(n_{p0} + \Delta n_p)(p_{p0} + \Delta p_p) + Bn_{p0}p_{p0}$$

$$= -Bn_{p0}\Delta p_p - Bp_{p0}\Delta n_p - B\Delta n_p\Delta p_p$$

At low injection level: $\Delta n_p << p_{p0} = N_A$

$$\frac{\partial n_p}{\partial t} \approx -Bp_{p0}\Delta n_p = -BN_A\Delta n_p$$

$$\frac{\partial \Delta n_p}{\partial t} = -\frac{\Delta n_p}{\tau_e}$$

$$\tau_e = \frac{1}{BN_A}$$

At high injection level: $\Delta n_p >> p_{p0} = N_A$

$$\frac{\partial n_p}{\partial t} \approx -Bp_p\Delta n_p = -BN_A(\Delta n_p)^2$$

$$\frac{\partial \Delta n_p}{\partial t} = -\frac{\Delta n_p}{\tau_e}$$

$$\tau_e = \frac{1}{B\Delta n_p}$$
### Recombination coefficients of representative semiconductors

<table>
<thead>
<tr>
<th>Material</th>
<th>Bandgap type</th>
<th>$\text{Br}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>In-direct</td>
<td>$1.79 \times 10^{-15} \text{ cm}^3/\text{s}$</td>
</tr>
<tr>
<td>Ge</td>
<td>In-direct</td>
<td>$5.25 \times 10^{-14} \text{ cm}^3/\text{s}$</td>
</tr>
<tr>
<td>GaP</td>
<td>In-direct</td>
<td>$5.37 \times 10^{-14} \text{ cm}^3/\text{s}$</td>
</tr>
<tr>
<td>GaAs</td>
<td>Direct</td>
<td>$7.21 \times 10^{-10} \text{ cm}^3/\text{s}$</td>
</tr>
<tr>
<td>GaSb</td>
<td>Direct</td>
<td>$2.39 \times 10^{-10} \text{ cm}^3/\text{s}$</td>
</tr>
<tr>
<td>InAs</td>
<td>Direct</td>
<td>$8.5 \times 10^{-11} \text{ cm}^3/\text{s}$</td>
</tr>
<tr>
<td>InSb</td>
<td>Direct</td>
<td>$4.58 \times 10^{-11} \text{ cm}^3/\text{s}$</td>
</tr>
</tbody>
</table>

What lifetime implies?

- Modulation bandwidth, for lifetime $\sim$ ns
- Maximum modulation $\sim$ GHz
Example: calculate radiative lifetime of GaAs & Si.

1. GaAs, assuming low level injection:
   
   \[ P \sim 10^{18} \text{ cm}^{-3} \leq N_A \]
   
   \[ \tau_r = \frac{1}{B r P} = \frac{1}{B r N_A} = \frac{1}{7.2 \times 10^{-10} \times 10^{18}} = 1.4 \text{ ns} \]

2. Si,
   
   \[ P \sim 10^{18} \text{ cm}^{-3} \leq N_A \]
   
   \[ \tau_r = \frac{1}{B r N_A} = \frac{1}{1.8 \times 10^{-15} \times 10^8} = 0.6 \text{ ms} \]

non-radiative combination

1. electron-hole pairs "recombine" through traps in the forbidden gap, which emit heat or multi-phonons also called "spare-charge recombination", which is a two-step process.
the Non-radiative recombination rate in space charge region

\[ R = \frac{N_i}{2e} e^{qU/2kT}, \quad \tau = \frac{1}{D^* V \theta N_t} \]

\( D^* \) : \( \sigma_p = \sigma_n \equiv \) hole & electron capture cross section

\( D^* = \sigma_n \), since trap is at roughly \( \frac{E_a}{2} \).

\( V \theta \) : thermal velocity

\( N_t \) : density of traps

2) Auger recombination

Collision of two electrons which knocks one electron down to valence band and the other to a higher energy state in CB.

\[ \tau_a = \frac{1}{C n_0^2}, \quad R_a = C N^3 \]

Auger recombination is important only at high injection level, \( C \) is material dependent.

Example, GaAs, \( \sigma = 5 \times 10^{-30} \text{ cm}^5 / \text{s} \).

In GaAs P, \( \sigma = 10^{-28} \text{ cm}^5 / \text{s} \).

For \( n_0 = 5 \times 10^{17} \text{ cm}^{-3} \), GaAs \( \tau_a = \frac{1}{5 \times 10^{-30} (5 \times 10^{17})^2} = 8 \mu s \)

In GaAs P \( \tau_a = \frac{1}{10^{-28} (5 \times 10^{17})^3} \approx 40 \text{ ns} \).
3) Interface Recombination

- dangling bonds at surface and material interface which forms miniband in energy gap

\[ \tau_s = \frac{W}{25} \]

\[ S = \text{interface recombination velocity} \]

Typical value of \( S \):
- GaAs \( \sim 10^6 \) cm/s
- InP \( \sim 10^3 \) cm/s

Heterojunction interface:
- Si/SiO\(_2\) \( \sim 10^4 \) cm/s
- GaAs/Al\(_x\)Ga\(_{1-x}\)As \( \sim 5000 \) cm/s (recently reduced to)
- InP/InGaAsP \( \sim 0.25 \) cm/s
  \[ 10^3 \text{ to } 10^4 \]
Quantum Efficiency (QE)

1. Internal QE: \( Q_i = \frac{\text{# of photons generated}}{\text{# electron-hole injected}} \)
\[
Q_i = \frac{R_T}{R_{\text{total}}} = \frac{\frac{\Delta n}{\tau}}{\frac{1}{\tau} + \frac{\Delta n}{\tau}} = \frac{1}{1 + \frac{\tau}{\tau_R}}
\]

\( R_{\text{total}} = R_T + R_{\text{r}} + R_{\text{t}} + R_{\text{a}} + R_{\text{s}} \)
\[
= \frac{1}{\tau} \frac{\Delta N}{N} + \frac{1}{\tau_T} \frac{\Delta n}{N} + \frac{\Delta C}{C_{\text{mho}}} + \frac{\alpha n}{2e}
\]

Example: \( Q_i \) for GaAs > Si:

GaAs: \( \tau_T \sim 1 \) ns, Assuming interface recombination dominates.
\[
S = 5 \times 10^4 \text{ cm/s}, \quad W \sim 0.3 \times 10^{-4} \mu \text{m}, \quad \Rightarrow \tau_R = 30 \text{ ns}
\]
\( Q_i \sim 97\% \)

For Si, \( \tau_T = 2 \times 10^{-4} \) s, \( \tau_R \approx 100 \text{ ns} \),
\( Q_i \sim 5 \times 10^{-4} \)

Conclusion: 1. \( \tau_T \) needs to be small enough.
2. Si is not a good light emitter.
**External Quantum Efficiency**

\[ \eta_e = \frac{\text{# photons emitted}}{\text{# eHP injected}} \]

- Depends on IQ and device structure

1. Back emission \( \sim 50\% \) loss through back

2. Fresnel Reflection:

\[ r = \frac{n_1 - n_2}{n_1 + n_2} = \frac{3.5 - 1}{3.5 + 1} = \frac{2.5}{4.5} = 40\% \]

3. Reabsorption:
4 total internal reflection

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

\[ \sin \theta_2 = \frac{n_2}{n_1} \sin \theta_1 \]

\[ \theta_2 = \theta_0 \]

Lambert law: Light measured will vary as the cosine of the angle off normal \( \theta_a \approx 16^\circ \)

Any light generated in the active region that larger than \( \theta_c = 16^\circ \), will not be emitted.

Efficiency due to TIR

\[ \frac{P_{out}}{P_{in}} = \frac{\int_0^{\theta_c} \sin \theta \, d\theta \, d\Omega \, d\theta_2 \, d\Omega_2 \pi}{\int_0^{\theta_c} \sin \theta \, d\theta \, d\Omega \, d\theta_2 \, d\Omega_2 \pi} = \frac{1}{2} \frac{2}{\sin \theta_c} \]

\[ = \frac{1}{2} \left( \frac{n_2}{n_1} \right)^2 \]
Include Fresnel reflections:

\[
\frac{P_{out}}{P_{in}} = (1-R) \cdot \frac{1}{2} \sin^2 \theta_c = 3\% \quad \leftarrow \text{Low quantum efficiency}
\]

Fundamental problem of LED for 35 years.

Solution:

* Textured structure

\[\text{Diagram: TEXTURED STRUCTURE} \quad \text{reflector}\]

* Grating
Communication LEDs

1. Structure:
   a. Surface emitting
   
   ![Surface Emitting Diagram]
   - electrode
   - Fiber

   ![Structure Diagram]
   - electrode

   b. Edge emitting
   - Multimode fiber
   - High coupling efficiency
   - Very thin active layer
   - Much of the light extends to cladding layer, low reabsorption

   - AR coating front facet
   - HR coating back facet

2. Emission Spectra
Example 3.3.1:

\[ L_n = \sqrt{D_n \tau_n} \approx 13 \mu m \]

\[ L_p = \sqrt{D_p \tau_p} \approx 3 \mu m \]

Minimum LED size? why?

\[ \Delta n_p = P_{n0} \left( e^{\frac{eV}{kT}} - 1 \right) \quad \Delta n_p = N_{p0} + \Delta n_p \]

\[ J_n = \frac{qd_n}{L_n} \frac{n_i^2}{N_A} \left( e^{\frac{qV}{kT}} - 1 \right) \]

\[ J_r = \left( \frac{qn_i W}{2\tau_n} + \frac{qn_i W}{2\tau_p} \right) \left( e^{\frac{V}{\eta kT}} - 1 \right) \]
Carrier confinement
\[ W_n \ll L_n = \sqrt{D_n \tau_n} \approx 13 \mu m \]
\[ W_p \ll L_p = \sqrt{D_p \tau_p} \approx 3 \mu m \]
Better light emitting efficiency

Band diagram

\[ \Delta E_g = \Delta E_c + \Delta E_v \]
\[ \Delta E_c = q\chi_2 - q\chi_1 \]

\[ V_0 = V_{01} + V_{02} \]

\[ \frac{V_{01}}{V_{02}} = \frac{\varepsilon_2 N_{A2}}{\varepsilon_1 N_{A1}} \]

\[ \varepsilon_1 E_1 = \varepsilon_2 E_2 \]
Carrier confinement:

\[ n_1 = n_2 e^{\frac{q(V_0 + \Delta E_c)}{kT}} \]

Reading Ch. 4.1-4.6, 4.9
Reduced density of States

6. Grain in a semiconductor

\[ E_z - E_c = \frac{\hbar^2 k_z^2}{2m^*_{e}} \]

\[ E_V - E_f = \frac{\hbar^2 k_V^2}{2m^*_{h}} \]

\[ k_c = k_V + k \text{ no phonon transitions} \]

\[ E_z - E_c = \frac{\hbar^2 k_z^2}{2m^*_{e}} (E_V - E_f) \]

\[ h\nu = E_z - E_f \]

\[ E_z - E_f = E_z - E_f + E_V - E_f + E_V - E_c \]

\[ = h\nu - (E_V - E_f) \neq - E_f \]

\[ = h\nu - E_f - (E_V - E_f) \]

\[ E_z - E_c = \frac{1}{1 + \frac{m_{e}^*}{m_{h}^*}} (h\nu - E_f) = \frac{m_{h}^*}{m_{e}^* + m_{h}^*} (h\nu - E_f) \]

\[ E_V - E_f = \frac{1}{1 + \frac{m_{e}^*}{m_{h}^*}} (h\nu - E_f) = \frac{m_{e}^*}{m_{e}^* + m_{h}^*} (h\nu - E_f) \]

\[ E_z - E_c = \frac{\hbar^2 k_z^2}{2m^*_{e}} (E_V - E_f) \]

\[ dE_z = -\frac{\hbar k_z}{m_e^*} dE_f \]

\[ f(h\nu) = \int f(E_z - E_f) \]

\[ f(h\nu) d(E_z - E_f) = P(h\nu) (dE_z - dE_f) \]

\[ dE = \hbar^2 \left( \frac{1}{m_e^*} + \frac{1}{m_h^*} \right) k dk \]

\[ \frac{dk}{dE} = \frac{1}{\hbar^2 \left( \frac{1}{m_e^*} + \frac{1}{m_h^*} \right) k} \]
Reduced density of States

\[ p(E) = \frac{4\pi k^2}{(2\pi)^3} \cdot \frac{dk}{dE} = \frac{1}{2\hbar^2 \beta^2} \cdot \frac{m^* M^*}{(E - E_g + \phi_h^e)^2}, \]

\[ \hbar k = \sqrt{2m^* \left( E - E_g \right)} \]

\[ p(h\nu) = \frac{1}{4\pi^2 \hbar^2} \cdot \exp \left( \frac{-1}{2m^* \hbar^2} \right) \cdot \left( h\nu - E_g \right)^3 \]

\[ \frac{m^* M^*}{m^* + M^*} \]

\[ p(h\nu) \rightarrow \text{reduced density of states, and reflects the fact the condition are placed on the recombination.} \]