Light Emitting Diode (LED) Principles

The Key mechanism of the Light emission in LEDs is Band - to - Band recombination (radiation)
Not ANY recombination produces the RADIATION. In case of *indirect* transitions, the recombination produces phonons rather than photons.

This is the case for Si.
Si cannot be used for efficient LEDs
Non-equilibrium conditions:
If the concentration of e-h pairs increases,

\[ n = \Delta n + n_0; \]
\[ p = \Delta p + p_0; \]

the recombination rate also increases:

\[ R_{sp} = B_r(n_o + \Delta n)(p_o + \Delta p) \]

\[ R_{SP}^0 = B_r n_0 p_0 \]

\[ R_{SP}^{ex} = B_r \left[ \Delta p \cdot n_0 + \Delta n \cdot p_0 + \Delta n \cdot \Delta p \right] \]

\[ R_{sp} = R_{sp}^o + R_{sp}^{ex} \]

Thermal generation rate G does not change as it does not depend on n and p

\( R^{ex} \) is the excess recombination rate producing the light
Forward biased p-n junction and light emission

Excess electrons

Excess holes

\[ n_p = n_{p0} e^{qV/kT} \]
\[ p_p = p_0 \]
\[ p_n n_n = p_{0n0} \cdot e^{qV/kT} \]
\[ p_n n_n = n_i^2 \cdot e^{qV/kT} \]

\[ p_n = p_{n0} e^{qV/kT} \]
\[ n_n = n_0 \]
\[ p_n n_n = p_{0n0} \cdot e^{qV/kT} \]
\[ p_n n_n = n_i^2 \cdot e^{qV/kT} \]
Under the forward bias,

The change in the electron concentration in the p-region:

\[
\Delta n_p = n_p - n_{p0} = n_{p0}(e^{qV/kT} - 1); \; \Delta p \approx 0
\]

\[
R_{SP}^{ex} = B_r \left[ \Delta p \cdot n_0 + \Delta n \cdot p_0 + \Delta n \cdot \Delta p \right] = B_r \Delta n \cdot p_0;
\]

\[
\Delta n = n_{p0}(e^{qV/kT} - 1); \; \rightarrow R_{SP}^{ex} = B_r n_{p0} p_{p0}(e^{qV/kT} - 1)
\]

\[
R_{SP}^{ex} = R_{SP}^0 (e^{qV/kT} - 1)
\]
Under the forward bias, 

The change in the hole concentration in the \textbf{n-region}: 

\[
\Delta p_n = p_n - p_{n0} = p_{n0}(e^{qV/kT} - 1); \quad \Delta n \approx 0
\]

\[
R_{SP}^{ex} = B_r \left[ \Delta p \cdot n_0 + \Delta n \cdot p_0 + \Delta n \cdot \Delta p \right] = B_r \Delta p \cdot n_0;
\]

\[
\Delta p = p_{n0}(e^{qV/kT} - 1); \quad \rightarrow R_{SP}^{ex} = B_r p_{n0}n_{n0}(e^{qV/kT} - 1)
\]

\[
R_{SP}^{ex} = R_{SP}^0 \left( e^{qV/kT} - 1 \right)
\]
Under the forward bias,

On both n- and p-sides of the forward-biased p-n junction the excess recombination rate increases exponentially with the bias:

\[ R_{SP}^{ex} = R_{SP}^0 (e^{qV/kT} - 1) \]

The forward current of p-n junction:

\[ I = I_S (e^{qV/kT} - 1) \]

Hence, recombination rate increases linearly with the forward current:

\[ R_{SP}^{ex} \sim I \]
The emitted photon energy,
\[ h \nu \approx \mathcal{E}_g; \]
(for band-to-band recombination).
Table 5.1  CHARACTERISTICS OF VISIBLE LIGHT-EMITTING DIODES (from M. G. Craford, "LEDs Challenge the Incandescents," *IEEE Circuits and Devices Magazine*, September 1992).

<table>
<thead>
<tr>
<th>Structure</th>
<th>Material</th>
<th>Bandgap type</th>
<th>Peak wavelength, nm (color)</th>
<th>Typical performance, lm/W</th>
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<tbody>
<tr>
<td>Homojunction</td>
<td>GaAsP</td>
<td>Direct</td>
<td>650 (red)</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>GaP: Zn, O</td>
<td>Indirect</td>
<td>700 (red)</td>
<td>0.4</td>
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<tr>
<td></td>
<td>GaAsP: N</td>
<td>Indirect</td>
<td>630 (red), 585 (yellow)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>GaP: N</td>
<td>Indirect</td>
<td>565 (yellow-green)</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>GaP</td>
<td>Indirect</td>
<td>555 (green)</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>SiC</td>
<td>Indirect</td>
<td>480 (blue)</td>
<td>0.04</td>
</tr>
<tr>
<td>Single heterojunction</td>
<td>AlGaAs</td>
<td>Direct</td>
<td>650 (red)</td>
<td>2</td>
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<tr>
<td>Double heterojunction</td>
<td>AlGaAs</td>
<td>Direct</td>
<td>650 (red)</td>
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<tr>
<td></td>
<td>AlGaP</td>
<td>Direct</td>
<td>620 (orange)</td>
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<td></td>
<td>AlInGaP</td>
<td>Direct</td>
<td>595 (amber)</td>
<td>20</td>
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<tr>
<td></td>
<td>AlInGaP</td>
<td>Direct</td>
<td>570 (yellow-green)</td>
<td>6</td>
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<tr>
<td></td>
<td>GaN</td>
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<td>450 (blue)</td>
<td>0.6</td>
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<tr>
<td>Double heterojunction with</td>
<td>AlGaAs</td>
<td>Direct</td>
<td>650 (red)</td>
<td>8</td>
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<td>transparent substrate</td>
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</table>
Typical LED structure:
LED efficiency

LED efficiency = Optical Power/Consumed power

The overall efficiency, consists, in general of 3 components:

- $\eta_{in}$ - injection efficiency,
- $\eta_r$ - recombination efficiency,
- $\eta_e$ - extraction efficiency.

(1) The Injection efficiency
determines how efficiently injected carriers contribute into recombination
When the injection occurs,

$$n = \Delta n + n_o$$

$$p = \Delta n + \frac{n_i^2}{n_o}$$

Light emission results from $\Delta n$ and $\Delta p$ recombination.
Injection efficiency as a function of junction doping

Consider n-side of the junction, close to the junction plane (x = 0):

\[ \Delta p = p_{n0} \left[ \exp \left( \frac{qV}{kT} \right) - 1 \right] \gg p_{n0}; \]
\[ \Delta n \cong 0; \quad n_{n0} \approx N_D; \]
\[ R_{n_{\text{ex}}} = B \times n_{n0} \times \Delta p \approx N_D \times \Delta p = N_D \times p_{n0} \left[ \exp \left( \frac{qV}{kT} \right) - 1 \right]; \]
\[ p_{n0} = n_i^2/n_0 \approx n_i^2/N_D; \]

Hence,
\[ R = B \times N_D \times n_i^2/N_D \times \exp(qV/kT) = R = B \times n_i^2 \times \exp(qV/kT) \]

1. \( R \) does not depend on the doping.
2. The \( R \) values are same for the p-side of the p-n junction.
3. Under “normal” injection conditions, the injection efficiency does not depend on the p- and n- doping levels.
**High-brightness LEDs:**

**Strong injection in asymmetric p-n junction.**

Consider $n^+ - p$ junction, $N_D >> N_A$

When the forward voltage applied is very high, $n_p \sim \exp(qV/kT) >> p_p$

This condition is referred to as “strong injection”
For strong injection into p-side:

\[ n_p(0) = n_{p0} \times \exp(qV/kT) \gg p_p(0); \]

Due to the charge neutrality:

\[ p_p(0) = n_p(0) \gg N_A \]

\[ R_p(0) = B \times n_p(0) \times p_p(0) \approx B \times n_p(0)^2 \]

\[ = B \times \left( n_i^2/N_A \right)^2 \times \exp(2qV/kT) \]

On the n-side, the injection still remains “normal”, because

\[ p_n < n_n \sim N_D \]

\[ R_n(0) = n_i^2 \times \exp(qV/kT) \]

Total recombination rate (on the n- and p-sides, at \( x = 0 \)):

\[ R(0) = B \times \left( n_i^2/N_A \right)^2 \times \exp(2qV/kT) + n_i^2 \times \exp(qV/kT) \]

The recombination rate increases with decreasing \( N_A \);
For strongly asymmetrical p-n junctions, the current formed by highly-doped region (the electron current in n$^+$ - p junction) contributes primarily into the recombination rate of LED

Therefore, the injection efficiency (for n$^+$ - p junction),

$$\eta_i = \frac{I_e}{I_0} = \frac{I_e}{I_e + I_h}$$

The current components of the p-n junctions are:

$$I_e = qA \frac{D_{e_n} p_0}{L_e} \left( e^{qV/kT} - 1 \right) \quad I_h = qA \frac{D_{h_p} n_0}{L_h} \left( e^{qV/kT} - 1 \right)$$

From these,

$$\eta_i = \left( qA \frac{D_{e_n} p_0}{L_e} \right) / \left( qA \frac{D_{e_n} p_0}{L_e} + qA \frac{D_{h_p} n_0}{L_h} \right) = \frac{D_{e_n} p_0 / L_e}{D_{e_n} p_0 / L_e + D_{h_p} p_0 / L_h}$$

To increase $\eta_i$, $p_{n0}$ has to be minimal, i.e. $N_D$ needs to be maximized
2) $\eta_r$ - recombination efficiency

In the presence of defects, some electron-hole pairs recombine without emitting photons: 
*non-radiative recombination.*

The rate of non-radiative recombination,

$$R_{nr} = \frac{\Delta n}{\tau_{nr}}$$

$\tau_{nr}$ is “non-radiative” recombination lifetime

The rate of radiative recombination,

$$R_r = \frac{\Delta n}{\tau_r}$$

$\tau_r$ is “radiative” recombination lifetime

Total recombination rate,

$$R_{sp} = R_r + R_{nr}$$

The recombination efficiency

$$\eta_r = \frac{R_r}{R_r + R_{nr}} = \frac{\tau_{nr}}{\tau_{nr} + \tau_r}$$
From
\[ R_{sp}^{ex} = B_{r}[n_0 p_0 + \Delta n (n_0 + p_0) + (\Delta n^2)] \]

We can express
\[ R_{sp}^{ex} = B_{r} \Delta n [n_0 + p_0 + \Delta n] \]

Using the lifetime definition,
\[ R_{sp}^{ex} = \frac{\Delta n}{\tau_r} \]

At very high excitation level,
\[ \Delta n \gg n_0, p_0, \text{ and} \]
\[ R_{sp}^{ex} = B_{r} (\Delta n)^2 \]
\[ \tau_r \approx \frac{1}{B_{r} \Delta n} \]

Radiative lifetime decreases with pumping \( \Rightarrow \) helps increasing recombination efficiency
Typical recombination efficiency – current dependence for p-n junction with high trap (defect) concentration

- Radiation efficiency increases
- Heating decreases the efficiency