Recombination Processes

Radiative vs. non-radiative
Relative carrier lifetimes

Light emitting diode basics

Concepts, operation; the eye and color
Device design challenges; performance metrics

LED practice

Early devices
  materials
  device structures
Fiber coupled devices
Resonant cavity devices
Modern devices
  high efficiency, high intensity advances
  new material advances
  white light sources

(continued from Lecture 17)

(history; LED evolution and revolution)

(getting heat and light out)
(nitrides)
Recombination models: radiative and non-radiative

- **Radiative recombination rate:**

\[
R_{rad} = r_{rad}(T) n p = B n p
\]

where we have followed the convention of writing the proportionality factor, \( r_{rad}(T) \), as \( B \).

If we assume we have a p-type sample, we define a radiative lifetime for the minority carriers as:

\[
R_{rad} = \frac{n}{\tau_{rad}}, \quad \text{where we define} \quad \tau_{rad} \equiv \frac{1}{Bp} \equiv \frac{1}{Bp_0}
\]

- **Non-radiative recombination rate:** Non-radiative recombination also depends on the \( np \) product, but since it occurs via mid-gap levels it is much less sensitive to the majority population, \( p \) in this case. Thus we define a non-radiative lifetime as

\[
R_{non-rad} = r_{non-rad}(T) n p = An = \frac{n}{\tau_{non-rad}}, \quad \text{with} \quad \tau_{non-rad} \equiv \frac{1}{A}
\]
Recombination models: net recombination

- **Net generation/recombination:** In thermal equilibrium generation and recombination balance:

\[ G_0 = R_0 = (r_{\text{rad}} + r_{\text{non-rad}})n_0p_0 = Bp_0n_0 + An_o \]

When we disturb thermal equilibrium by injecting excess carriers and/or having current, we can have net generation or recombination, and a population change:

\[ \frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial J_e}{\partial x} + G_0 + g_{\text{ext}}(x,t) - Bnp - An \]

Using our equilibrium relation, we can write this as:

\[ \frac{\partial n}{\partial t} - \frac{1}{q} \frac{\partial J_e}{\partial x} = g_{\text{ext}}(x,t) - B(np - n_0p_0) - A(n - n_0) \]

It is convenient to define excess carrier populations:

\[ n' \equiv (n - n_0), \quad p' \equiv (p - p_0) \]
Recombination models: net recombination, cont.

With these definitions, we have

\[
\frac{\partial n'}{\partial t} - \frac{1}{q} \frac{\partial J_e}{\partial x} \approx g_{ext}(x,t) - [B(p_o + p') + A]n'
\]

To obtain this we assumed quasineutrality, \( n' \approx p' \), and extrinsic p-type, \( p_o \gg n_o \).

If we assume low-level injection, defined as \( p' \ll p_o \), then we can neglect \( p' \) relative to \( p_o \) and write:

\[
\frac{\partial n'}{\partial t} - \frac{1}{q} \frac{\partial J_e}{\partial x} \approx g_{ext}(x,t) - [Bp_o + A]n' = g_{ext}(x,t) - \frac{n'}{\tau_{\text{min}}}
\]

where the minority carrier lifetime is defined as:

\[
\tau_{\text{min}} \equiv \frac{1}{(Bp_o + A)}
\]
Recombination models: net recombination, cont.

It is important to relate the total minority carrier lifetime to the radiative and non-radiative lifetimes we introduced earlier:

\[
\frac{1}{\tau_{\text{min}}} \equiv Bp_o + A = \frac{1}{\tau_{\text{rad}}} + \frac{1}{\tau_{\text{non-rad}}}
\]

Finally, note that if we have high-level injection, we find that the lifetime decreases with injection level:

\[
\tau_{\text{min}} = \frac{1}{B(p_o + p') + A}
\]

Note also that the it is the radiative lifetime that is decreasing and thus that the fraction of carriers recombining radiatively is increasing.
Light emitting diodes: current-output relationships

Assume we have an LED where the efficient radiative emission occurs on the p-side of the device (a typical situation). The optical power out of this LED is:

\[ P_{\text{out}} = \eta_{\text{ext}} P_{\text{generated}} = \eta_{\text{ext}} h \nu \int_{\text{dev}} A \frac{n'}{\tau_{\text{rad}}} dx \]

where:
- \( h \nu \): energy per photon
- \( \eta_{\text{ext}} \): extraction or external efficiency (the fraction of photons generated that get out)
- \( A \): device cross-section area normal to current
- and the integral is the total number of photons generated per unit time in the device.

This integral can be related to the total diode current and the minority carrier current on the p-side.
We return to:

\[
\frac{\partial n'}{\partial t} - \frac{1}{q} \frac{\partial J_e}{\partial x} = g_{ext}(x,t) - \frac{n'}{\tau_{\text{min}}}
\]

In the steady state, with no external generation term this becomes:

\[
\frac{1}{q} \frac{\partial J_e}{\partial x} = \frac{n'}{\tau_{\text{min}}}
\]

And the integral in the output power equation becomes:

\[
\int_o^{w_p} \frac{n'}{\tau_{\text{rad}}} \, dx = \frac{1}{q} \frac{\tau_{\text{min}}}{\tau_{\text{rad}}} \int_o^{w_p} \frac{\partial J_e}{\partial x} \, dx = \frac{1}{q} \frac{\tau_{\text{min}}}{\tau_{\text{rad}}} \left[ J_e(0^+) - J_e(w_p) \right]
\]

Inserting this, we arrive at:

\[
P_{\text{out}} = \frac{\hbar \nu}{q} \eta_{\text{ext}} A \frac{\tau_{\text{min}}}{\tau_{\text{rad}}} \left[ J_e(0^+) - J_e(w_p) \right]
\]
Light emitting diodes: current-output relationships, cont

Finally, we recognize that it is useful conceptually to identify several of the terms in this result as efficiencies. Doing so we write:

\[ P_{out} = h \nu \frac{i_D}{q} \eta_{ext} \frac{A[J_e(0^+) - J_e(w_p)]}{i_D} \frac{\tau_{min}}{\tau_{rad}} = h \nu \frac{i_D}{q} \eta_{ext} \eta_i \eta_{rad} \]

where:

- \( h \nu \): energy per photon
- \( \eta_{ext} \): extraction or external efficiency (the fraction of photons generated that get out)
- \( \eta_i \): current efficiency (the fraction of the total diode current that is current into the p-side of the device and that recombines there before getting to the contact)
- \( \eta_{rad} \): radiative efficiency (the fraction of electron current that recombines radiatively)

Identifying these efficiencies is useful because doing so helps us understand how to make the device better. We will next look at them each in turn, ...bottom to top...
**Light emitting diodes: radiative efficiency**

The radiative efficiency is defined as:

\[
\eta_{\text{rad}} \equiv \frac{\tau_{\text{min}}}{\tau_{\text{rad}}} = \frac{1}{\tau_{\text{rad}}} + \frac{1}{\tau_{\text{non-rad}}} = \frac{1}{1 + \tau_{\text{rad}}/\tau_{\text{non-rad}}}
\]

From this we confirm our intuition that a short radiative lifetime and long non-radiative lifetime are best. This is largely a question of using the right materials, and making sure they are high quality.

We can also write \( \eta_{\text{rad}} \) in terms of \( A \) and \( B \):

\[
\eta_{\text{rad}} \equiv \frac{\tau_{\text{min}}}{\tau_{\text{rad}}} = \frac{B(p_o + p')}{B(p_o + p') + A} = \frac{1}{1 + A/[B(p_o + p')]} \]

from this we see that driving the device to high level injection may help. (We say "may" because this may also lead to heating which will reduce the non-radiative lifetime.)
Light emitting diodes: radiative efficiency, cont

Material choices:

- **Direct band gap** - the radiative lifetime is much shorter for direct band gap materials:
  
  \[
  B: \quad 10^{-11} \text{ to } 10^{-9} \text{ cm}^3\text{s}^{-1} \quad \text{for direct gap}
  \]
  \[
  10^{-15} \text{ to } 10^{-13} \text{ cm}^3\text{s}^{-1} \quad \text{for indirect gap}
  \]

Sample values:

- GaAs: \(7.2 \times 10^{-10}\)
- Si: \(1.8 \times 10^{-15}\)
- Ge: \(5.25 \times 10^{-14}\)

Common materials:

- **IR**: GaAs, InGaAsP, GaInNAs
- **Visible**: GaAsP, InGaP, InGaAsP, GaN, GaAlInN

- **Gap level transitions** - there are a few examples of useful radiative transitions via levels in the energy gap
  
  - GaP: Zn-O pairs (red)
  - N-valence band (green)
  - GaAs: Si-donor to Si-acceptor (980 nm)
Light emitting diodes: current efficiency

The current efficiency is the fraction of the total diode current that is due to the desired minority carriers (electrons injected into the p-side in the present example) that recombine before reaching the ohmic contact:

\[ \eta_i = \frac{A}{i_D} \left[ J_e(0^+) - J_e(w_p) \right] \]

We can make the current efficiency approach 100% by taking the following precautions:

- **Use asymmetric doping:** this insures injection into the appropriate side of the device. \( N_{Dn} >> N_{Ap} \)
- **Make the diodes wide:** this insures that the carriers recombine before reaching the contacts. \( w_p << L_e \)
- **Use heterojunctions:** to increase injection efficiency and to shield carriers for ohmic contacts
Light emitting diodes: extraction efficiency

The extraction efficiency, how much of the radiation actually leaves the device, is the most difficult issue for many LEDs. There are several contributions:

1. Total internal reflection
2. Internal (re)absorption
3. Blocking by contacts

Because of the refractive index of most semiconductors is high, 3.5 being a typical value, Item 1 is a major issue. The critical angle for total internal reflection is only 16° at a semiconductor-to-air boundary. Spontaneous radiation (which is what we are dealing with) is directed uniformly in all directions, and the fraction hitting a flat surface within the critical angle, \( \Theta_{\text{crit}} \), is:

\[
\eta_{\text{ex}} = \left( \sin^2 \Theta_{\text{crit}} \right) / 4
\]

Evaluating this for \( n = 3.5 \), we find that only 2% of the light can escape the solid!
Light emitting diodes: fighting total internal reflection

Total internal reflection can be alleviated if the device is packaged in a domed shaped, high index plastic package:

If the device is fabricated with a substrate that is transparent to the emitted radiation, then light can be extracted from the 4 sides and bottom of the device as well as from the top. This increases the extraction efficiency by a factor of 6!
Light emitting diodes: fighting total internal reflection, cont.

Other solutions to the total internal reflection that are not as widely used as these are:

Thin devices with roughened surfaces: The idea is that if there is very little internal (re)absorption of the emitted light, the light will bounce around inside the device until it hits the surface at an angle within the critical angle. If the surface is rough, the chance of this happening is increased.

Resonant cavity LEDs: If a one-dimensional photonic crystal (a distributed Bragg reflector) is placed on the bottom of the device, the light emitted downward will be redirected up.

Superluminescent emitting LEDs: If a device is driven strongly enough, there can be some stimulated emission, and this will be highly directed, as we shall see when we talk about laser diodes. This can be used to increase an LEDs emission.

None of these ideas work as well as using a transparent substrate, collecting the light from all sides of a device, and putting the device in a high-index package positioned in a suitable reflector.
**Light emitting diodes: historical perspective**

LEDs are a very old device, and were the first commercial compound semiconductor devices in the marketplace. Red, amber, and green LEDs (but not blue) were sold in the 1960's, but main research focus was on laser diodes, and little LED research was done after the 1970's.

Things changed dramatically in the 1990's, in part because of new materials developed in the search for red and blue lasers, InGaP/GaAs, GaInAlN/GaN in part because of packaging innovations, improved heat sinking and advanced reflector designs in part due to advances in wafer bonding, and transparent substrates for improved light extraction in part due to the diligence of LED researchers. taking advantage of advances in other fields
III-V quarternaries: InGaAsP

Early GaAsP red LEDs grown on linearly graded buffer on GaAs

Modern InGaAlP red LEDs grown lattice-matched on GaAs, and transferred to GaP substrates
The III-V wurtzite quarternary: GaInAlN
Light emitting diodes -

typical spectra

- LED emission - typ. 20 nm wide

- Important spectra for comparison with LED spectrum
Light emitting diodes - human eye response

Φν: Luminous flux (lm)

Violet  Blue  Green  Yellow  Orange  Red

400  450  500  550  600  650  700  750

510 nm  610 nm
Light emitting diodes - Red and Amber LEDs

- Red LEDs
- Yellow/Amber LEDs
Light emitting diodes - Conventional green LEDs; Burrus-type

- Green LEDs
- LED designed to couple efficiently to a fiber (Burrus geometry)
Light emitting diodes - illustrating recent advances

(Images Deleted)

C. G. Fonstad. 4/03

Lecture 18 - Slide 22