ECE 440
Lecture 30: LEDs and Lasers

Class Outline:

• Light Emitting Diodes
• Lasers
• Semiconductor Lasers
Key Questions

- What is an LED and how does it work?
- How does a laser work?
- How does a semiconductor laser work?

Things you should know when you leave...
Light Emitting Diodes

How do light emitting diodes work?

• The basic structure is a p-n diode.

• Under forward bias, minority carriers are injected on both sides of the junction.

• Near the junction we have a collection of excess carriers greater than the equilibrium concentrations.

• Under these conditions recombination will take place as the minority carriers diffuse away from the interface.

• In an indirect material like Si or Ge, the recombination mechanism is normally through the emission of a phonon.

• In a direct band gap semiconductor, the transition from the conduction band to the valence band may be through the release of a photon with an energy of that of the band gap.
Light Emitting Diodes

What happens if we use a **heterostructure**?

• We can greatly **improve the efficiency** of the LED.

• Use wider band gap materials to confine the carriers to a central, light-producing region.

• Increasing the carrier confinement will increase the radiative efficiency by reducing the radiative recombination lifetime.

• If we reduce the central region to 10 nm or smaller, we form a quantum well.

• This pushes the carrier densities to higher levels and can result in higher efficiency.

• The quantization of energy levels can change the radiative energy shifting it to energies higher than the band gap.
Light Emitting Diodes

How much variation in the photon energy can I get by using a heterostructure?

We can obtain much of the electromagnetic spectrum by using different compounds.

- GaN has a band gap of 3.4 eV which gives us the ultraviolet part of the spectrum.

- InSb has a band gap of 0.18 eV which gives us the infrared part of the spectrum.

As an example, examine $\text{GaAs}_x\text{P}_{1-x}$...

- Band gap varies from 1.42 eV (infrared) to 2.26 eV (green).

- Linear variation in gap until $x=0.4$ when the material becomes indirect.

- Add extra nitrogen and light returns in the yellow to green portion.

- Nitrogen impurity binds electrons tightly but spreads out momentum uncertainty and momentum conservation rules can be circumvented.
Light Emitting Diodes

How have LEDs improved over time...
Light Emitting Diodes

So how efficient are these LEDs?

• Efficiency depends on the quality of the material.

• Defects will lead to non-radiative recombination.

• Even if the internal efficiency is high, we can still have an inefficient device.

• LEDs have a wide angular distribution of the light emitted.

• Depending on the shape of the semiconductor air interface some light will be totally internally reflected.

LEDs are made with a dome which acts as a lens to extract more light.
**Light Emitting Diodes**

LEDs are part of many applications...

They are part of:

- Displays
- Traffic lights
- DVD and CD players
- TV remotes...

Why would there be any interest in short wavelength emitters (blue-green LED)?

- InGaAlN is a compound that is direct over all alloy compositions and offers light in the blue-green region.

- If we can make RBG emitters we can make intense white light sources which are twice as efficient as current light bulbs.

- These would last between 2 and 50 times longer.
Lasers

Laser is an acronym for **Light Amplification by Stimulated Emission of Radiation**.

The laser is a source of highly directional, monochromatic, coherent light.

- Can be a continuous beam of low to medium power.
- Can provide short pulses of intense light providing millions of watts.
- Used frequently in fiber optic communications.

We already know about the radiative recombination process…

But this type of recombination occurs randomly and are referred to as **spontaneous emission**.

How do we stimulate the system to make a radiative transition between levels?
Lasers

The stimulus is provided by the photon field containing photons of the proper wavelength...

Suppose we have an electron in E2 to E1.

Put the electron in an intense field of photons each with the same energy and phase.

• This induces the electron to drop from one energy level to the other contributing a photon that is in phase with the rest of the photons.

• The process will continue producing a stream of monochromatic and coherent radiation.

• The process is highly quantum mechanical in nature

Can we simplify the description of the process?
Lasers

Assume we have \( n_1 \) carriers in \( E_1 \) and \( n_2 \) carriers in \( E_2 \)...

From earlier, we know that in thermal equilibrium the distribution of states is given by the Boltzmann factor...

\[
\frac{n_2}{n_1} = e^{-(E_2 - E_1)/kT} = e^{-\frac{hv_{12}}{kT}}
\]

Rate of stimulated emission is proportional to the instantaneous number of electrons in \( n_2 \) and to the total energy density...

\[
B_{12}n_1 \rho(v_{12}) = A_{21}n_2 + B_{21}n_2 \rho(v_{12})
\]

Absorption = spontaneous + stimulated emission

No energy required to transition from upper state to lower state, but the reverse is not true.

In equilibrium the emission is still very small.

So how do we enhance the stimulated emission?
Lasers

If we use a resonant optical cavity, the photon density can build up to a large value through multiple internal reflections at certain frequencies...

To obtain more stimulated emission, we need the population of the upper state to be greater than that of the lower state...

\[
L = \frac{m\lambda}{2}
\]

Population inversion or negative temperature

In summary, we need two things to force stimulated emission to dominate over spontaneous emission and absorption...

1. Optical resonant cavity to encourage the field to build up.
2. Means of creating population inversion
Lasers

Perhaps most importantly we can use them in fiber optic communications...

- 25 microns in diameter.
- Outer core is SiO$_2$.
- Inner core is Ge doped glass.

• Light is transmitted along the fiber by total internal reflection.

• There are losses associated with each reflection leading to attenuation.

• Not all wavelengths are attenuated similarly.

• Around 1.3 and 1.55 microns attenuation is less.
Semiconductor Lasers

How do we make a laser out of a semiconductor?

Form a p-n junction between two degenerately doped materials and apply a forward bias.

For a large enough bias, significant numbers of electrons and holes are injected.

The region around the junction is far from depleted so that if the conduction band and valence band are sufficiently populated, then we may obtain population inversion...

How do we describe this state?

Since we are so far out of equilibrium we need to use the quasi-Fermi levels to obtain the correct carrier concentrations in each of the regions.
Semiconductor Lasers

Carrier concentrations are going to be larger than in equilibrium and we are not in equilibrium, so we need quasi-Fermi levels...

\[ n = N_c e^{-(E_c - F_n)/kT} = n_i e^{(F_n - E_i)/kT} \]

\[ p = N_v e^{-(F_p - E_v)/kT} = n_i e^{(E_i - F_p)/kT} \]

We have high concentrations of electrons and holes near the junction which decay exponentially to the bulk value.

The separation of \( F_n \) and \( F_p \) gives a measure of how far from equilibrium the system is biased.

To obtain population inversion, frequently the separation between quasi-Fermi levels is greater than the band gap in the inversion area.

But we must be careful in that we are not dealing with a simple two level system in a semiconductor...
Semiconductor Lasers

The basic definition for population inversion still holds...

But in a semiconductor, bands of energy levels are available for transitions.

Transitions take place from the bottom of the conduction band and the top of the valence band.

Or, another way, is to say they take place from $F_n$ to $F_p$.

Population inversion condition for any transition:

For band-band transitions:

$$ (F_n - F_p) > h\nu $$

We should note that in choosing materials for lasers, the material should both be direct and be doped easily.
**Semiconductor Lasers**

What does the emission spectra look like?

Under forward bias, we will get a mixture of spontaneous emission and stimulated emission.

The two limits on the photon energies emitted are the band gap and the difference in the quasi-Fermi levels.

At low current, we get spontaneous emission spectrum.
Now begin to increase the bias and current flowing through the p-n junction...

For moderate current we have an integer number of half-wavelengths in the resonant cavity the begin to contribute...

\[ m = \frac{2Ln}{\lambda_0} \]

\[ \frac{dm}{d\lambda_0} = -\frac{2Ln}{\lambda_0^2} + \frac{2L}{\lambda_0} \frac{dn}{d\lambda_0} \]

\[ -\Delta\lambda_0 = \frac{\lambda_0^2}{2Ln} \left(1 - \frac{\lambda_0}{n} \frac{dn}{d\lambda_0}\right)^{-1} \Delta m \]

• Let \( \Delta m = -1 \) and we can calculate the change in wavelength between successive modes \( m \) and \( m-1 \).
• Achieve population inversion and we get monochromatic light.