Other Devices from p-n junctions

• Memory (5/7 -- Glenn Alers)

Electron to Photon conversion devices
• LEDs and SSL (5/5)
• Lasers (5/5)
• Solid State Lighting (5/5)

Photon to electron conversion devices
• Photodectors (5/12)
• Solar Cells (5/14)
• Displays and HW Review (5/19)

HW#3 on capacitors, transistors and LEDs/Lasers due 5/12
HW#4 on photodetectors and solar cells due 5/19
Midterm #2 5/21
Electron-Hole Generation / Recombination

Photon absorbed in band-gap
   Electron elevated to conduction band
   Hole remains in valence band
   Energy cost = $E_g$

Electron-hole recombination
   Electron recombines with hole
   Energy is emitted as photon
   Energy of photon = $E_g$

Photon stimulates electron in conduction
   Electron-hole recombine $\rightarrow$ photon
   Two coherent photons emitted
   Laser amplification
Electrical Light Emission

Simple p-n junction

Engineered p-n junction = heterojunction

Recombination Zone
~ within diffusion length
~ depletion region

Electron / holes recombine in recombination zone

More electrons/holes in forward bias

Light emitted in forward bias

Smaller bandgap in center

Traps electrons and holes

Increased recombination

More efficient conversion
Spontaneous and Stimulated Emission

When an electron decays without external influence it is said to be due to "spontaneous emission." The phase associated with the photon that is emitted is random. If a number of electrons were put into an excited state somehow and then left to relax, the resulting radiation would be spectrally limited but the individual photons would not be in phase with one another. This is also called fluorescence.

Lasers: Stimulated Emission

Other photons (i.e. an external electromagnetic field) will affect an atom's state. The quantum mechanical variables mentioned above are changed. Specifically the atom will act like a small electric dipole which will oscillate with the external field. One of the consequences of this oscillation is it encourages electrons to decay to the lower energy state. When it does this due to the presence of other photons, the released photon is in phase with the other photons and in the same direction as the other photons. This is known as stimulated emission.
Einstein Coefficients

In 1917, about 9 years before the development of the relevant quantum theory, Einstein postulated on thermodynamic grounds that the probability for spontaneous emission, $A$, was related to the probability of stimulated emission, $B$, by the relationship

$$A/B = \frac{8\pi h \nu^3}{c^3}$$

From the development of the theory behind blackbody radiation, it was known that the equilibrium radiation energy density per unit volume per unit frequency was equal to

$$\rho(\nu) = \frac{8\pi h \nu^3}{c^3}$$

Einstein argued that equilibrium would be possible, and the laws of thermodynamics obeyed, only if the ratio of the $A$ and $B$ coefficients had the value shown above. This ratio was calculated from quantum mechanics in the mid 1920's. In recognition of Einstein's insight, the coefficients have continued to be called the Einstein $A$ and $B$ coefficients.
Einstein Coefficients

There are three Einstein coefficients, denoted $A_{12}$, $A_{21}$, and $B_{12}$. $A_{12}$ is the spontaneous emission coefficient, which may be calculated from first principles using quantum mechanics knowing the wavefunctions and the first-order perturbation to the Hamiltonian caused by an atom's dipole moment. $B_{12}$ is the stimulated emission coefficient.

In radiative equilibrium, spontaneous emission is balanced by spontaneous absorption,

\[ A_{12} \equiv -A_{21}. \]  

Let $n$ be the number of particles in a state, then the absorption rate is

\[ \text{[absorption rate]} = n_1 B_{12} b_\nu, \]

where $b_\nu$ is the Planck brightness and is the occupancy of state 1. In the Rayleigh-Jeans limit,

\[ B_{12} = \frac{g_2}{g_1} \frac{c^2}{2h\nu^3} A_{21}, \]

Where $g_1$ and $g_2$ are the degeneracies of states 1 and 2, respectively, $c$ is the speed of light, $h$ is Planck's constant, and $\nu$ is the frequency of radiation.

\[ \text{[spontaneous emission rate]} = n_2 A_{21}. \]

A photon of the appropriate frequency can cause emission of a photon with the same energy and in the same direction. This is the phenomenon responsible for the operation of a laser, and is known as stimulated emission.

\[ \text{[stimulated emission rate]} = n_2 B_{21} b_\nu \]

\[ B_{21} = \frac{c^2}{2h\nu^3} A_{21}. \]
If the number of light sources in the excited state is given by $N$, the rate at which $N$ decays is:

$$\frac{\partial N}{\partial t} = -A_{21} N$$

$$N(t) = N(0)e^{-A_{21}t} = N(0)e^{-\Gamma_{\text{rad}}t}$$

where $N(0)$ is the initial number of light sources in the excited state, $t$ is the time and $\Gamma_{\text{rad}}$ is the radiative decay rate of the transition, and $A_{21}$ (referred to as an Einstein A coefficient) is the rate of spontaneous emission.

where $B_{21}$ is a proportionality constant for stimulate emission in this particular atom (referred to as an Einstein B coefficient), and $\rho(\nu)$ is the radiation density of photons of frequency $\nu$. 
Lasers: light amplification by stimulated emission of radiation

Laser diodes consist of a p-n diode with an active region where electrons and holes recombine resulting in light emission. In addition, a laser diode contains an optical cavity where stimulated emission takes place. The laser cavity consists of a waveguide terminated on each end by a mirror.

Stimulated emission is the process by which an electron, perturbed by a photon having the correct energy, may drop to a lower energy level resulting in the creation of another photon. The perturbing photon is seemingly unchanged in the process (cf. absorption), and the second photon is created with the same phase, frequency, polarization, and direction of travel as the original.

Structure of an edge-emitting laser diode.
Solid State Laser

Laser: Coherent emission of light
(emission at same frequency and in phase)

Two requirements:
- Population inversion = large population of electrons in excited state
- Stimulated emission = incident photon induces transition, synchronous output photon

Current from forward biased diode populates level

Heterojunctions permit stronger population inversion

Resonator to enhance stimulated emission
Lasing Condition

Combined with the waveguide losses, stimulated emission yields a net gain per unit length, $g$. The number of photons can therefore be maintained if the roundtrip amplification in a cavity of length, $L$, including the partial reflection at the mirrors with reflectivity $R_1$ and $R_2$ equals unity.

This yields the following lasing condition:

$$\text{Roundtrip amplification} = e^{2gL R_1 R_2} = 1$$

If the roundtrip amplification is less than one then the number of photons steadily decreases. If the roundtrip amplification is larger than one, the number of photons increases as the photons travel back and forth in the cavity and no steady state value would be obtained. The gain required for lasing therefore equals:

$$g = \frac{1}{2L} \ln \frac{1}{R_1 R_2}$$

Initially, the gain is negative if no current is applied to the laser diode as absorption dominates in the waveguide. As the laser current is increased, the absorption first decreases and the gain increases.
Laser: Output Power

The current for which the gain satisfies the lasing condition is the threshold current of the laser, $I_{th}$. Below the threshold current very little light is emitted by the laser structure. For an applied current larger than the threshold current, the output power, $P_{out}$, increases linearly. The output power therefore equals:

$$P_{out} = \eta \frac{h\nu}{q} (I - I_{th})$$

where $h\nu$ is the energy per photon. The factor, $\eta$, indicates that only a fraction of the generated photons contribute to the output power of the laser as photons are partially lost through the other mirror and throughout the waveguide.
A laser diode consists of a cavity, defined as the region between two mirrors with reflectivity $R_1$ and $R_2$, and a gain medium, usually a quantum well. The optical mode originates in spontaneous emission, which is confined to the cavity by the waveguide. This optical mode is amplified by the gain medium and partially reflected by the mirrors. The modal gain depends on the gain of the medium, multiplied with the overlap between the gain medium and the optical mode which we call the confinement factor, $\Gamma$, or:

$$\text{modal gain} = g(N)\Gamma$$

Lasing occurs when the round trip optical gain equals the losses. For a laser with modal gain $g(N) \Gamma$ and waveguide loss, $\alpha$, this condition implies:

$$R_1R_2 \exp[2(g(N) - \alpha)L] = 1$$

where $L$ is the length of the cavity. The distributed loss of the mirrors is therefore:

$$\text{mirror loss} = \frac{1}{L} \ln \frac{1}{\sqrt{R_1R_2}}$$
Longitudinal modes in the laser cavity correspond to standing waves between the mirrors. If we assume total reflection at the mirrors this wave contains $N/2$ periods where $N$ is an integer. For a given wavelength $\lambda$ and a corresponding effective index, $n_{\text{eff}}$, this yields:

$$N = \frac{2n_{\text{eff}}L}{\lambda}$$

Ignoring dispersion effects,

$$N = \frac{2n_{\text{eff}}L}{\lambda_1} \quad N + 1 = \frac{2n_{\text{eff}}L}{\lambda_2} \quad \Delta\lambda = 2Ln_{\text{eff}}\left(\frac{1}{N} - \frac{1}{N + 1}\right) \approx \frac{\lambda_1^2}{2Ln_{\text{eff}}^2}$$

Longer cavities therefore have closer spaced longitudinal modes. An edge emitting (long) cavity with length of 300 $\mu$m, $n_{\text{eff}} = 3.3$, and $\lambda = 0.8 \mu$m has a wavelength spacing $\Delta\lambda$ of 0.32 nm while a surface emitting (short) cavity of 3 $\mu$m has a wavelength spacing of 32 nm. These wavelength differences can be converted to energy differences using:

$$\Delta E = \frac{hc}{2Ln_{\text{eff}}} = E_{ph} \frac{\Delta\lambda}{\lambda_2}$$
Emission, Absorption and modal gain

The analysis of a semiconductor laser diode requires a detailed knowledge of the modal gain, which quantifies the amplification of light confined to the lasing mode. To find the modal gain, one starts from the requirement that the emission as well as absorption of photons, must conserve both energy and momentum of all particles involved in the process. The conservation of energy requires that the photon energy equals the difference between the electron and hole energy:

\[
E_{ph} = E_n - E_p \\
E_n = E_c + E_{1n} + \frac{\hbar^2 k_n^2}{2m_n^*} \\
E_p = E_v - E_{1p} + \frac{\hbar^2 k_p^2}{2m_p^*}
\]

The conservation of momentum requires that the electron momentum equals that of the empty state it occupies in the valence band plus the momentum of the photon:

\[
k_n = k_p + k_{ph}
\]

\[
E_{ph} = E_{g,qw1} + \frac{\hbar^2 k_n^2}{2m_r^*} \\
\frac{1}{m_r} = \frac{1}{m_n^*} + \frac{1}{m_p^*}
\]

\[
E_n = E_c + E_{1n} + \left(E_{ph} - E_{g,qw1}\right) \frac{m_r^*}{m_n^*} \\
E_p = E_v - E_{1p} - \left(E_{ph} - E_{g,qw1}\right) \frac{m_r^*}{m_p^*}
\]
Emission, Absorption and modal gain

The emission and absorption spectra ($\beta(E_{ph})$ and $\alpha(E_{ph})$) of a quantum well depend on the density of states and the occupancy of the relevant states in the conduction and valence band. Since the density of states in the conduction and valence band is constant in a quantum well, the emission and absorption can be expressed as a product of a maximum emission and absorption rate and the probability of occupancy of the conduction and valence band states, namely:

$$\beta(E_{ph}) = \beta_{\text{max}} f_n(E_n) \left[1 - f_p(E_p)\right]$$

$$\alpha(E_{ph}) = \alpha_{\text{max}} \left[1 - f_n(E_n)\right] f_p(E_p)$$

Stimulated emission occurs if an incoming photon triggers the emission of another photon. The net gain in the semiconductor is the stimulated emission minus the absorption. The maximum stimulated emission equals the maximum absorption since the initial and final states are simply reversed so that the transition rates as calculated based on the matrix elements are identical. The net gain is then given by:

$$g(E_{ph}) = \beta(E_{ph}) - \alpha(E_{ph}) = g_{\text{max}} \left[f_n(E_n) - f_p(E_p)\right]$$

where the maximum stimulated emission and the maximum absorption were replaced by the maximum gain, $g_{\text{max}}$. 
Laser Diode

A laser diode is a laser where the active medium is a semiconductor similar to that found in a light-emitting diode. The most common and practical type of laser diode is formed from a p-n junction and powered by injected electric current. These devices are sometimes referred to as injection laser diodes to distinguish them from (optically) pumped laser diodes, which are more easily produced in the laboratory.

The first to demonstrate coherent light emission from a semiconductor diode is Robert N. Hall and his team at the General Electric research center in 1962. The first visible wavelength laser diode was demonstrated by Nick Holonyak, Jr. later in 1962.

In the early 1960s liquid phase epitaxy (LPE) was invented by Herbert Nelson of RCA Laboratories. By layering the highest quality crystals of varying compositions, it enabled the demonstration of the highest quality heterojunction semiconductor laser materials for many years. LPE was adopted by all the leading laboratories, worldwide and used for many years. It was finally supplanted in the 1970s by molecular beam epitaxy and organometallic chemical vapor deposition.
Solid State Laser

Final structure:
- Light emission perpendicular to current flow
- Light emission parallel to substrate

Alternate design:
Mirrors = interference reflectors
Laser design

Reflective Mirrors on both sides

Confine photons to stimulate emission (remain coherent)

99% reflective = 1% out

For emission from thin layer:

thickness < wavelength

Waveguide with total internal reflection
Laser Diode: Double Heterostructure

A layer of low bandgap material is sandwiched between two high bandgap layers. One commonly-used pair of materials is gallium arsenide (GaAs) with aluminium gallium arsenide (AlxGa(1-x)As). Each of the junctions between different bandgap materials is called a heterostructure, hence the name "double heterostructure laser" or DH laser.

The advantage of a DH laser is that the region where free electrons and holes exist simultaneously is confined to the thin middle layer. This means that many more of the electron-hole pairs can contribute to amplification. In addition, light is reflected from the heterojunction; hence, the light is confined to the region where the amplification takes place.
If the middle layer is made thin enough, it acts as a quantum well. This means that the vertical variation of the electron's wavefunction, and thus a component of its energy, is quantised. The efficiency of a quantum well laser is greater than that of a bulk laser because the density of states function of electrons in the quantum well system has an abrupt edge that concentrates electrons in energy states that contribute to laser action.

Lasers containing more than one quantum well layer are known as multiple quantum well lasers. Multiple quantum wells improve the overlap of the gain region with the optical waveguide mode.

Further improvements in the laser efficiency have also been demonstrated by reducing the quantum well layer to a quantum wire or to a "sea" of quantum dots.
Vertical-cavity surface-emitting lasers (VCSELs) have the optical cavity axis along the direction of current flow rather than perpendicular to the current flow as in conventional laser diodes. The active region length is very short compared with the lateral dimensions so that the radiation emerges from the surface of the cavity rather than from its edge. The reflectors at the ends of the cavity are dielectric mirrors made from alternating high and low refractive index quarter-wave thick multilayer.
LEDs (light emitting diodes)

LEDs were discovered in 1907 by the British experimenter H. J. Round of Marconi Labs, using a crystal of silicon carbide and a cat's-whisker detector. Russian Oleg Vladimirovich Losev independently created the first LED in the mid 1920s; his research was distributed in Russian, German and British scientific journals, but no practical use was made of the discovery for several decades. Rubin Braunstein of the Radio Corporation of America reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys in 1955. In 1961, experimenters Bob Biard and Gary Pittman working at Texas Instruments, found that GaAs emitted infrared radiation when electric current was applied and received the patent for the infrared LED.

Inorganic: p-n junctions

Organic: usually MIM structure, can be p-i-n
LED Efficiency

Efficiency Improvement
2x improvement / 3 years

Most are red / orange
(up-converted to blue/green)

MAJOR REVOLUTION 1992
GaN (blue) invented

Blue light → white light

Florescent light still best
(short lifetime)

Prediction: Florescent lights replaced by LEDs within 10 years
Inorganic LEDs
Inorganic LEDs: Solid State Lighting

Spectrum of a “white” LED clearly showing blue light which is directly emitted by the GaN-based LED (peak at about 465 nm) and the more broadband Stokes-shifted light emitted by the Ce3+:YAG phosphor which emits at roughly 500–700 nm.
Organic LEDs