Summary of Lecture 8 – I

1. Atoms have discrete energy levels (for outer electrons) but solids have energy bands where electrons and holes reside
2. Electrons in conduction band from thermal generation or from donor atoms in lattice
3. Holes in valence band from thermal generation or from acceptor atoms in lattice
4. Electrons and holes viewed as wave packets in motion (can’t localize these charge carriers) with separate effective masses (m*)
5. Semiconductors have forbidden bandgaps which dominate their physical properties
6. Holes have positive charge and electrons have negative charge which under low doping conditions can be treated as classical particles (but don’t look too closely at the “particle”)

Representing the Density of States of Semiconductor Bands

For a semiconductor:

- Conduction band is empty at $T = 0$ K
- Valence band is completely filled by electrons at $T = 0$ K
- No electron states in the bandgap

Note: A filled band can’t conduct current

https://en.wikipedia.org/wiki/Band_gap
Conduction & Valence Bands in Semiconductors

https://www.scienceabc.com/innovation/what-are-semiconductors-and-how-do-they-work.html
Electron-Hole Pairs in Intrinsic Semiconductor

An intrinsic semiconductor behaves like an insulator at $T = 0$ K.

At $T > 0$ K thermally generated electron-hole pairs.

https://vidyarthiacademy.in/vidyarthiacademy/cbsenotes/xiiphys/12-phys-cbsenotes-14-semiconductors.php
Fermi Energy Level in Intrinsic Semiconductor

Intrinsic Concentration $n_i$

$E_F = \text{midgap energy}$

Fermi energy or Fermi level

Fermi-Dirac Distribution for Electrons in a Material

\[
f(E) = \frac{1}{1 + \exp((E - E_F)/K_BT)}
\]

- \( f(E) < 1 \) for \( E < E_F \)
- \( f(E) > 0 \) for \( E > E_F \)
- \( f(E) = \frac{1}{2} \) for \( E = E_F \)

**Fermi Level**

https://sites.google.com/site/puenggphysics/home/unit-5/fermi-dirac-function
Fermi-Dirac Distribution and Maxwell-Boltzmann Approximation

http://www.iue.tuwien.ac.at/phd/mwagner/node28.html
Direct Bandgap vs. Indirect Bandgap Semiconductors

*E- k* diagrams

\[ k = \frac{2\pi}{\lambda} \]

Wave Vector or Crystal Momentum

Direct bandgap semiconductors

Indirect bandgap semiconductors

http://edetec106.blogspot.com/2016/01/differentiate-between-direct-and.html
PN-Junctions in Semiconductors

PN-junctions have many **applications**:  
1. Rectifiers  
2. Variable capacitance  
3. Switching  
4. Voltage reference  
5. Solar cells  
6. **Photodetectors**  
7. AC-to-DC conversion  
8. On-chip thermometer  
9. Generators of negative resistance (oscillation)  
10. **LED and laser sources**  
11. Noise generators  
12. High voltage protection
The Formation of a PN-Junction

The pn-junction is covered in Senior, 3rd edition, in Section 6.3.1, pp. 309 to 311.

http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/pnjun.html
The Formation of a PN-Junction

$$E_0 = V_T \cdot \ln \left( \frac{N_D N_A}{n_i^2} \right)$$

$$E_o = -V_T = \frac{kT}{q}$$

https://www.electronics-tutorials.ws/diode/diode_2.html
Majority Carriers and Minority Carriers in Doped Semiconductor

Law of Mass Action

\[ n_0 p_0 = n_i^2 \]

\begin{align*}
\text{n-type: } n_0 &= N_D, \quad p_0 = \frac{n_i^2}{N_D} \\
\text{p-type: } p_0 &= N_A, \quad n_0 = \frac{n_i^2}{N_A}
\end{align*}

In silicon the intrinsic carrier concentration at \( T = 300 \text{ K} \) is

\[ n_i (\text{cm}^{-3}) = 1.01 \times 10^{10} \text{ pairs/cm}^3 \]

\[ n_i^2 (\text{cm}^{-6}) = 1.02 \times 10^{20} (\text{pairs/cm}^3)^2 \]

Based upon the Boltzmann distribution.

https://www.pveducation.org/pvcdrom/pn-junctions/equilibrium-carrier-concentration
The Potential Barrier in a PN-Junction

https://www.researchgate.net/figure/Abrupt-p-n-junction-in-thermal-equilibrium-adapted-from-Ref-51-a-Space-charge_fig3_283081246
Semiconductor PN-Junction Both Forward and Reverse Bias

When we bring P-type & N-type together a depletion zone is created around the junction. This produces a barrier, blocking charge flow.

https://giphy.com/gifs/work-ei2AYYW8qdZyo
Spontaneous Emission From Recombination at PN-Junction

A $pn$-junction under forward bias giving spontaneous emission of photons.

From: Section 6.3.4, Figure 6.11, in Senior, 3rd ed.
Spontaneous Emission From Electroluminescence

We require a direct bandgap semiconductor and the transition is known as “band-to-band” recombination. Under forward bias the excess minority carrier populations decay from band-to-band recombination. Thus, the energy of the photon is approximately equal to the bandgap energy $E_G$.

$$E_G = hf = \frac{hc}{\lambda}$$

- $c$ = velocity of light
- $\lambda$ = wavelength

$$\lambda [\mu m] = \frac{1.24}{E_G [eV]}$$

Called electroluminescence (from spontaneous emission) in diode.

From: Section 6.3.4, in Senior, 3rd ed.
Band Structure in Momentum Space ($k$ Space)

**Direct Bandgap**
- $\Gamma > L$

**Indirect Bandgap**
- $\Gamma > L$

**Direct Bandgap**
- $L > \Gamma$

*For example, Si and Ge*

*For example, GaAs*

[Image: Band Structure in Momentum Space ($k$ Space)]

A phonon is an excited state in the quantum mechanical quantization of the modes of vibrations of elastic structures of interacting particles.

\[ k = k_n = \frac{2\pi n}{Na} \quad \text{for } n = 0, \pm 1, \pm 2, \ldots \pm \frac{N}{2}. \]
Energy-Momentum Diagrams Showing Transitions

From: Section 6.3.3, Figure 6.13 (page 314), in Senior, 3rd ed.
Maintaining Conservation of Energy and Momentum

But phonons have energy which must be accounted for

Scenario 1

Scenario 2

Direct Bandgap  Indirect Bandgap  Indirect Bandgap

GaAs  photon  Si  photon

Photon Emission is Slower in Indirect Gap Materials

The radiative minority carrier lifetime is

$$\tau_r = \frac{1}{B_r(n + p)}$$

where $B_r$ is recombination coefficient (cm$^3$sec$^{-1}$), and $n$ and $p$ are the respective minority carrier and majority carrier concentrations.

Example 6.4 (page 315)

Compare an indirect gap semiconductor (Si) with a direct bandgap semiconductor (GaAs). Assume for both that $(n + p) = 1 \times 10^{18}$ cm$^{-3}$.

For silicon, $B_r = 1.79 \times 10^{-15}$ cm$^3$sec$^{-1}$, thus

$$\tau_r(Si) = \frac{1}{B_r(n + p)} = \frac{1}{1.79 \times 10^{-15} (1 \times 10^{18})} = \frac{1}{1790} = 0.56 \text{ milliseconds}$$

For gallium arsenide, $B_r = 7.21 \times 10^{-10}$ cm$^3$sec$^{-1}$, thus

$$\tau_r(GaAs) = \frac{1}{B_r(n + p)} = \frac{1}{7.21 \times 10^{-10} (1 \times 10^{18})} = \frac{1}{7.21 \times 10^8} = 1.39 \text{ nanoseconds}$$

From Section 6.3.3, pp. 313 to 316 in Senior, 3rd ed.
Sources for Coherent and Incoherent Light

https://www.ee.co.za/article/choose-laser-based-sensor.html/ret-april-2016-fig2
Properties of a Laser Diode

- **Coherence**: It is a crucial property of laser, that exists due to stimulated emission. It simply denotes that the wavelength of the waves of emitted light is in phase. With an ordinary light source (e.g., LED), it is not coherent because it is generated by spontaneous emission of photons.

- **Monochromaticity**: Monochrome means it has a single wavelength. Waves having single wavelength denotes a single color.

- **Brightness**: Brightness of a light is basically the power per unit surface area per unit solid angle. Due to continuous reflections, a light of high intensity and more power is produced by laser diodes.

- **Directionality**: A laser light is highly directional this means it does not exhibit much beam divergence. Directionality in a laser diode is achieved because the emitted photons undergo multiple reflections between the mirrors.

Direct Bandgap Semiconductor With Stimulated Emission Possible

Band to band transition

Thus, we can use for both LEDs and Semiconductor lasers

https://www.slideshare.net/KamalKhan822/solids-conductors-insulators-semiconductors
Direct Bandgap Semiconductor Diode Emitting Spontaneously

Individual Packaging of LEDs

https://lastminuteengineers.com/light-emitting-diode-led/
Light Emitting Diodes and Commonly Found Packaging

https://elprocus.wordpress.com/2013/07/25/led-architecture-and-design-concepts/
Coupling LED light into an Optical Fiber

https://www.skipprichard.com/ask-questions-to-improve-your-leadership/