ECE 488: Compound Semiconductors

M,W,F 11:00 – 11:50, 3013 ECEB
Professor John Dallesasse
2114 Micro and Nanotechnology Laboratory
Tel: (217) 333-8416
E-mail: jdallesa@illinois.edu
Office Hours: Tuesday 13:00 – 14:00
Lecture 8: September 9th, 2016
Assignments

• Reading from “Compound Semiconductors and Devices – An Introduction”
  – Wed 9/7: §’s 2.5, 2.5.1, 2.5.2, 2.5.3, 2.5.4, 2.5.5, 3.1, 3.1.1, 3.1.2, 3.1.3
  – Fri 9/9: §’s 3.2, 3.2.1, 3.2.2, 3.2.3
  – Mon 9/12: §’s 3.3, 3.3.1, 3.3.2
• HW1 Posted 8/31, Due Friday 9/9
• HW2 (Chapter 2): To Be Posted
Today’s Agenda

• Bonding: Ionic, Covalent, Mixed (Brief Discussion)
• Major Semiconductor Crystal Structures
• Reciprocal Lattice, Diffraction Condition, and the Brillouin Zone
**Tentative Schedule [1]**

<table>
<thead>
<tr>
<th>AUG 22: Introductions, Objectives, Class Outline, Policies</th>
<th>AUG 24: Motivation, Intro to Quantum Theory</th>
<th>AUG 26: Infinite Square &amp; Triangle Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUG 29: Potential Steps, Coulomb Well (Hydrogen Atom), Atomic Bonding</td>
<td>AUG 31: Crystal Structures, Diffraction</td>
<td>SEP 2: Reciprocal Space, Diffraction Condition</td>
</tr>
<tr>
<td>SEP 5: LABOR DAY NO CLASS</td>
<td>SEP 7: The Brillouin Zone, Band Structures, Density of States</td>
<td>SEP 9: Bloch Theorem, Empty Lattice Model</td>
</tr>
<tr>
<td>SEP 12: Band Gaps</td>
<td>SEP 14: Kronig-Penny Model</td>
<td>SEP 16: Effective Mass, Bloch Oscillations, Band Structure</td>
</tr>
</tbody>
</table>

**Guideline Only: Subject to Change**
Atomic Bonding
Ionic Bonds

- The ionic bonds are formed through the electron transfer action as demonstrated in NaCl crystals.
- The electron configurations of sodium (Na) and chlorine (Cl) are
  \[ \text{Na} - 1s^2 2s^2 2p^6 3s^1; \quad \text{Cl} - 1s^2 2s^2 2p^6 3s^1 3p^5 \]
- \( \text{Na}^+ \) ion and \( \text{Cl}^- \) ion are formed when transferring one electron from Na atom to Cl atom.

- The Coulomb attraction force between \( \text{Na}^+ \) ions and \( \text{Cl}^- \) ions keeps these ions together in a NaCl crystal.
- Coulomb repulsive force between similar ions prevents the crystal from collapsing.
- \[ E_{\text{total}} = E_{\text{coulomb att}} + E_{\text{repulsive}} \]
Ionic Bonds (2)

- Attributes of ionic crystals:
  - Non-directional;
  - Forms close atomic packing;
  - Crystal structure (either FCC or BCC) determined by the size difference between ions.
  - Large band gap energy; $E_g(\text{NaCl}) = 8.4$ eV.
Covalent Bonding

Covalent Bond Formation

- Nitrogen molecules ($N_2$):
  Nitrogen has an electron configuration of $1s^22s^22p^3$. When forming $N_2$ molecule, they share six valence electrons to form “electron pair” bond.

- Hydrogen ion ($H_2^+$):

$$\psi(1s) = \frac{1}{\sqrt{\pi a_o^3}} \exp\left(-\frac{r}{a_o}\right)$$

(a) Atomic orbitals
Bonding and Antibonding States

Wave functions

Anti-symmetric: (anti-bonding)

\[ E_{PE} = E_{n-n} \]

Symmetric: (bonding)

\[ E_{PE} = -E_{e-n} + E_{n-n} \]

Attraction

Repulsion
Electron Pair Bonding

“Electron pair” bond in H\(_2\) molecule:
The shared valence electrons with symmetric electron wave have the identical quantum numbers of \(n, l,\) and \(m.\) They have to have opposite spin orientation, or, anti-parallel spins \(s=\pm l/2\) to comply with Pauli’s exclusion principle. This is known as the electron-pair bonding.

Electron configuration in N\(_2\):

\[2p^6\]

First \(↓\)  second \(↓\)
Ammonia Molecule

- $NH_3$ molecule ($N-1s^22s^22p^3; H-1s^1$)

- Conclusions:
  - The bonding energy is lowered by an accumulation of electrons in the region of lower potential energy between two nuclei.
  - Electrons are shared but do not specifically belong to a particular nucleus.
  - Spin of the two electrons must have anti-parallel arrangement, i.e., electron-pair bonding.
Directional Properties of Covalent Bonds

A strong covalent bonding is formed by shared electrons with maximum wave function overlap. The bond structure depends on the shape of interacting wave functions. The wave function of $p$-state has an angular dependent shape as in the hydrogen model $[\Theta(\theta)\Phi(\phi)]$:

$$\psi_{210} \propto \cos \theta; \quad \psi_{211} \propto \sin \theta \exp(i\phi); \quad \psi_{21\bar{1}} \propto \sin \theta \exp(-i\phi)$$

The linear combination of exponential decaying $\psi_p$’s leads to

$$\begin{align*}
\psi_{211} + \psi_{21\bar{1}} &\propto \sin \theta \cos \phi \\
\psi_{211} - \psi_{21\bar{1}} &\propto \sin \theta \sin \phi \\
\psi_{210} &\propto \cos \theta
\end{align*}$$

and

$$\begin{align*}
x &= r \sin \theta \cos \phi \\
y &= r \sin \theta \sin \phi \\
z &= r \cos \theta
\end{align*}$$

Letting $R(r) = rf(r)$, we can express $\psi_p$’s as

$$\psi_{px} = xf(r), \quad \psi_{py} = yf(r), \quad \psi_{pz} = zf(r).$$

Each of the three $p$ wave functions extends along a specific axis.
The interaction of $2s$ and three $2p$ atomic orbitals will form a new set of covalent orbitals with maximum overlap of electron distribution.
Covalent Bond Polarity

- When forming covalent bonds, only a certain orientations of $\psi_p$ will provide a maximum overlap of electron distributions with $\psi_s$. The bond structure is determined principally by **minimizing electron-pair repulsions**.
- Example- $NH_3$ molecule ($N-1s^22s^22p^3; H-1s^1$): The bonds will take the form of a tetrahedral arrangement. The possible combined $2s$ and three $2p$ atomic orbits are shown.
Methane $sp^3$ Hybrid Orbitals

- Methane ($CH_4$) molecule ($C-1s^22s^22p^2$; $H-1s^1$):

  ![Diagram of $sp^3$ Hybrid Orbitals]

  - There are two unpaired electrons available for four hydrogen valence electrons.
  - Recall that $|\psi_{2p}|^2 r^2$ occupies a lower energy state than $|\psi_{2s}|^2 r^2$. It’s possible to have one $2s$ electron of carbon atom be elevated to $2p$ state. This will raise the total energy of the system.
  - However, when forming pair bonds with electrons from four hydrogen atoms, the total energy will be lowered.

  ![Diagram of $sp^3$ Hybrid Orbitals]

  - The $2s^12p^3$ configuration is called “$sp^3$ hybrid orbits”.

Tetrahedral Bond Alignment: $sp^3$ Hybrids

- The $sp^3$ bonding structure of methane ($CH_4$) molecule is a tetrahedron.
- The C-H bonds are lying along [111], [111], [111], and [111] directions to minimize repulsive forces between electrons of hydrogen atoms.
- The wave functions of the tetrahedron bands can be derived by linear combination of $s$- and $p$-state wave functions.

\[
\begin{align*}
\psi_{111} &= \frac{1}{2}(\psi_s + \psi_x + \psi_y + \psi_z) \\
\psi_{111} &= \frac{1}{2}(\psi_s - \psi_x - \psi_y + \psi_z) \\
\psi_{111} &= \frac{1}{2}(\psi_s + \psi_x - \psi_y - \psi_z) \\
\psi_{111} &= \frac{1}{2}(\psi_s - \psi_x + \psi_y - \psi_z)
\end{align*}
\]

- The methane molecule has no free covalent bond to form crystal.
Semiconductor Crystal Structures
Semiconductor Crystals

- Si \((1s^22s^22p^63s^23p^2)\) uses \(sp^3\) bonds to bond four neighbors to form tetrahedron structures. The tetrahedrons are the building blocks of the diamond structure (Si crystal).

The binding orbital between the nearest neighbors is a linear combination of hybridized orbital from each atom. In pure silicon, the electrons shared in a bond spend, on the average, ‘equal time’ on each atom. This leads to a pure covalent bond.
Mixed Ionic-Covalent Bonds

- GaAs crystals:
  \[ \text{Ga}(1s^22s^22p^63s^23p^63d^{10}4s^24p^1), \text{As} \ (1s^22s^22p^63s^23p^63d^{10}4s^24p^3) \]
  On average, there are 4 bonding valence electrons per Ga atom sharing with 4 As atoms to form \( sp^3 \) covalent bonds. The \( sp^3 \) bonds are formed by transferring one electron from As to Ga.
  \[ \text{Ga}(4s^14p^2)^+ + \text{As} \ (4s^14p^4) \rightarrow \text{Ga}(4s^14p^3)^- + \text{As} \ (4s^14p^3)^+ \]
  This process leads to the formation of Ga\(^-\) and As\(^+\) ions. The bonding electrons spend a greater fraction of time on the anion as in partially ionic bond.
- Thus,
  \[ \psi_b \sim \psi_{\text{covalent}} + \lambda \psi_{\text{ionic}} \]
  \( \lambda \) is the ‘ionicity parameter’.
- Ionicity (\( f_i \)):
  \[ f_i = \frac{\lambda^2}{1 + \lambda^2} \]
- Electronegativity:
  Power of an atom to attract an electron to itself in a compound. The electronegativity difference (\( \Delta E \)) is well correlated with the ionicity of a compound.
Electronegativity, Ionicity and Structure

- Effect of electronegativity difference ($\Delta E$) between bonding atoms:

<table>
<thead>
<tr>
<th>$\Delta E=0$ (covalent bond)</th>
<th>$\Delta E$ (intermediate) (polar covalent bond)</th>
<th>$\Delta E$ (large) (ionic)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Covalent Bond" /></td>
<td><img src="image" alt="Polar Covalent Bond" /></td>
<td><img src="image" alt="Ionic Bond" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>III-V</th>
<th>Structure</th>
<th>Ionicity</th>
<th>III-V</th>
<th>Structure</th>
<th>Ionicity</th>
<th>III-V</th>
<th>Structure</th>
<th>Ionicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlN</td>
<td>W</td>
<td>0.45</td>
<td>GaN</td>
<td>W</td>
<td>0.50</td>
<td>InN</td>
<td>W</td>
<td>0.58</td>
</tr>
<tr>
<td>AlP</td>
<td>ZB</td>
<td>0.31</td>
<td>GaP</td>
<td>ZB</td>
<td>0.37</td>
<td>InP</td>
<td>ZB</td>
<td>0.42</td>
</tr>
<tr>
<td>AlAs</td>
<td>ZB</td>
<td>0.27</td>
<td>GaAs</td>
<td>ZB</td>
<td>0.31</td>
<td>InAs</td>
<td>ZB</td>
<td>0.36</td>
</tr>
<tr>
<td>AlSb</td>
<td>ZB</td>
<td>0.43</td>
<td>GaSb</td>
<td>ZB</td>
<td>0.26</td>
<td>InSb</td>
<td>ZB</td>
<td>0.32</td>
</tr>
</tbody>
</table>

(W: wurtzite structure; ZB: zincblende structure)
2.4.1. Diamond Structure

- Silicon and germanium crystals have diamond structure.
- Diamond structure is described as two interpenetrating FCC structures that are displaced relative to one another along the body diagonal. For a FCC lattice constant $a$, the displacement from the origin is $\left(\frac{1}{4}, \frac{1}{4}, \frac{1}{4}\right) a$.

![Diamond Structure Diagram](image)

Bond length $= \sqrt{3}a/4$
Diamond Structure (2)

- Diamond structure can also be constructed using 4 tetrahedrons.
  - In one unit cell, the bottom half consists of two tetrahedral structures joined diagonally.
  - The top half has the same structure but is oriented at 90° with respect to the bottom half diagonal.
Zinc Blende

- Zinc blende crystal structure is closely related to diamond structure except the neighboring atoms are different. In each tetrahedron, the center atom is different from the corner atoms. The crystal structure can be seen as an intersection of two types of BCC’s along the diagonal line.

- Zinc blende structure is less symmetry than the diamond structure, which leads to many characteristics not seen in crystal of diamond structure.
Piezoelectric Effect in III-Vs

- In GaAs, along [111], the atoms arranged in layered structure with different atoms in alternating layers.

- A compression along [111] will cause charges to move closer and induce an electric field. This cause a piezoelectric effect in GaAs, but not in silicon, which has a diamond structure. The induced electric field causes extra carrier scattering and affects carrier mobility.
Wurtzite Structure

- Difference between FCC close packing and hexagonal close packing (HCP) structures

Layer A

Layer B

FCC: The layer sequence along [111] is ABCABCA..., where spheres in layer C is located at holes through both layer A and B.

HCP: The layer sequence along [0001] is simply ABABA....
Structural Relationship: HCP, Wurtzite

- The basic HCP structure is formed by interleaving two hexagonal structures, along the $c$-axis. The displacement of the second hexagonal lattice from the first hexagonal lattice origin is $c/2$ along $c$-axis and $2a/3$ and $a/3$ in $a_1$ and $a_2$ directions, respectively.

- The wurtzite structure is formed by interleaving two HCP structures, having different atoms A (Zn) and B (S), along the same $c$-axis. The displacement of the A-type lattice from the B-type is $3c/8$, which is the bond length and $c = a\sqrt{8/3}$.
- Each atom has 4 nearest neighbors of the other type, at the corners of a regular tetrahedron of which it occupies the center.
Wurtzite Unit Cell & Structure

Unit cell of a Wurtzite structure

\[ c = a\sqrt{8/3} \]
Zinc Blende Relationship to Wurtzite

- The origin of the wurtzite structure is due to the ionic bonding nature. The cation and the anion located in the adjacent layers tend to align along the $c$-axis by the strong Coulomb attraction force.
- For zinc blende structures, the repulsive force between bonding electrons dominates the bond formation. The two types of atoms in the (111) planes next to each other tend to minimize the repulsive force by maximizing the separation. The projection of the resulted bond of the top layer is oriented in between the two bonds in the bottom layer.
Crystal Diffraction
Crystal Diffraction

The periodic lattice structure of a crystal can be deduced by diffraction experiments using x-ray, electrons and atoms. The diffraction spectrum is formed by waves scattered from the periodic lattice points through constructive interference.

\[
n\lambda = 2d_{hkl}\sin\theta \quad (n = 1, 2, 3, \ldots)
\]

Path length difference is integer multiple of \(\lambda/2\)
Either (a) Laue method (*frequency domain*) or (b) rotating crystal method (*time domain*) provides information about the crystal lattice structure.
FTIR

(Optical Measurement Technique)
Fourier Transform Infrared Spectroscopy

- An FT-IR instrument uses a system called an interferometer to collect a spectrum.
- The moving mirror moves back and forth at a constant velocity. The beam from the moving mirror travels a different distance than the beam from the fixed mirror. When two beams are combined an interference pattern, called an interferogram, is created.
- The interferogram signal transmitted through the sample is collected by the detector. The detector reads the information about every wavelength in the infrared range simultaneously.
- The detector signal is then send to a computer for processing using Fourier Transform algorithm. The detected interogogram in time-domain is converted into a spectrum in frequency-domain (wavenumber, cm⁻¹).
The wavelet of interferogram in time domain contains all the Fourier components of the frequency domain information.

Fourier transformation can be used to derive the information in frequency domain from the interferogram (time domain) and vise versa.
Agenda for Next Class

• Reciprocal Lattice
• The Brillouin Zone
Thank You!
### Periodic Table of the Elements

#### Table Description:

- **Atomic Symbol**: Represents the element.
- **Atomic Number**: Indicates the proton number.
- **Atomic Mass**: Represents the average atomic mass.

#### Periodic Table:

<table>
<thead>
<tr>
<th>Period</th>
<th>Group</th>
<th>Element</th>
<th>Symbol</th>
<th>Atomic Number</th>
<th>Mass (Da)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>IA</td>
<td>Sodium</td>
<td>Na</td>
<td>11</td>
<td>22.9900</td>
</tr>
<tr>
<td>I</td>
<td>IA</td>
<td>Potassium</td>
<td>K</td>
<td>19</td>
<td>39.0983</td>
</tr>
<tr>
<td>I</td>
<td>IA</td>
<td>Rubidium</td>
<td>Rb</td>
<td>37</td>
<td>85.4678</td>
</tr>
<tr>
<td>I</td>
<td>IA</td>
<td>Cs</td>
<td>Cs</td>
<td>55</td>
<td>132.90547</td>
</tr>
<tr>
<td>II</td>
<td>IIA</td>
<td>Magnesium</td>
<td>Mg</td>
<td>12</td>
<td>24.3050</td>
</tr>
<tr>
<td>II</td>
<td>IIA</td>
<td>Calcium</td>
<td>Ca</td>
<td>20</td>
<td>40.0780</td>
</tr>
<tr>
<td>II</td>
<td>IIA</td>
<td>Strontium</td>
<td>Sr</td>
<td>38</td>
<td>87.62</td>
</tr>
<tr>
<td>II</td>
<td>IIA</td>
<td>Barium</td>
<td>Ba</td>
<td>56</td>
<td>137.327</td>
</tr>
<tr>
<td>III</td>
<td>IIIA</td>
<td>Aluminum</td>
<td>Al</td>
<td>13</td>
<td>26.9815</td>
</tr>
<tr>
<td>III</td>
<td>IIIA</td>
<td>Silicon</td>
<td>Si</td>
<td>14</td>
<td>28.0855</td>
</tr>
<tr>
<td>III</td>
<td>IIIA</td>
<td>Germanium</td>
<td>Ge</td>
<td>32</td>
<td>72.64</td>
</tr>
<tr>
<td>III</td>
<td>IIIA</td>
<td>Tin</td>
<td>Sn</td>
<td>50</td>
<td>118.71</td>
</tr>
<tr>
<td>III</td>
<td>IIIA</td>
<td>Lead</td>
<td>Pb</td>
<td>82</td>
<td>207.2</td>
</tr>
<tr>
<td>IV</td>
<td>IVA</td>
<td>Boron</td>
<td>B</td>
<td>5</td>
<td>10.81</td>
</tr>
<tr>
<td>IV</td>
<td>IVA</td>
<td>Carbon</td>
<td>C</td>
<td>6</td>
<td>12.0107</td>
</tr>
<tr>
<td>IV</td>
<td>IVA</td>
<td>Nitrogen</td>
<td>N</td>
<td>7</td>
<td>14.0067</td>
</tr>
<tr>
<td>IV</td>
<td>IVA</td>
<td>Oxygen</td>
<td>O</td>
<td>8</td>
<td>15.9994</td>
</tr>
<tr>
<td>IV</td>
<td>IVA</td>
<td>Fluorine</td>
<td>F</td>
<td>9</td>
<td>18.9984</td>
</tr>
<tr>
<td>IV</td>
<td>IVA</td>
<td>Neon</td>
<td>Ne</td>
<td>10</td>
<td>20.1797</td>
</tr>
<tr>
<td>V</td>
<td>VA</td>
<td>Neon</td>
<td>Ne</td>
<td>10</td>
<td>20.1797</td>
</tr>
<tr>
<td>V</td>
<td>VA</td>
<td>Fluorine</td>
<td>F</td>
<td>9</td>
<td>18.9984</td>
</tr>
<tr>
<td>V</td>
<td>VA</td>
<td>Oxygen</td>
<td>O</td>
<td>8</td>
<td>15.9994</td>
</tr>
<tr>
<td>V</td>
<td>VA</td>
<td>Nitrogen</td>
<td>N</td>
<td>7</td>
<td>14.0067</td>
</tr>
<tr>
<td>V</td>
<td>VA</td>
<td>Carbon</td>
<td>C</td>
<td>6</td>
<td>12.0107</td>
</tr>
<tr>
<td>V</td>
<td>VA</td>
<td>Boron</td>
<td>B</td>
<td>5</td>
<td>10.81</td>
</tr>
<tr>
<td>VI</td>
<td>VIA</td>
<td>Nitrogen</td>
<td>N</td>
<td>7</td>
<td>14.0067</td>
</tr>
<tr>
<td>VI</td>
<td>VIA</td>
<td>Oxygen</td>
<td>O</td>
<td>8</td>
<td>15.9994</td>
</tr>
<tr>
<td>VI</td>
<td>VIA</td>
<td>Fluorine</td>
<td>F</td>
<td>9</td>
<td>18.9984</td>
</tr>
<tr>
<td>VI</td>
<td>VIA</td>
<td>Neon</td>
<td>Ne</td>
<td>10</td>
<td>20.1797</td>
</tr>
<tr>
<td>VI</td>
<td>VIA</td>
<td>Carbon</td>
<td>C</td>
<td>6</td>
<td>12.0107</td>
</tr>
<tr>
<td>VI</td>
<td>VIA</td>
<td>Boron</td>
<td>B</td>
<td>5</td>
<td>10.81</td>
</tr>
</tbody>
</table>

#### Notes:

- For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

---

**Design and Interface Copyright © 1997 Michael Dayah (michael@dayah.com). http://www.ptable.com/**
Common Semiconductors

Fig. 21.4. Room-temperature bandgap energy versus lattice constant of common elemental and binary compound semiconductors.
Contact Information & Website

Professor John M. Dallesasse
2114 Micro and Nanotechnology Laboratory
Office Hours: Tuesdays, 1-2 pm, 2114 MNTL
Office: (217) 333-8416
jdallesa@illinois.edu

John Carlson (TA)
3034 Micro and Nanotechnology Laboratory
Office Hours: Thursdays, 10-11 am, 3034 ECEB
jcarls21@illinois.edu

Website:
https://courses.engr.illinois.edu/ece488/
Course Objectives
Course Objectives

• Develop a working knowledge of compound semiconductor materials and devices
• Provide a foundation for future advanced physical electronics courses
• Provide basic device knowledge to support a career in wireless communications or photonics
• Provide sufficient background such that you can begin to read and understand the literature on compound semiconductor materials and devices
Course Outline
Course Outline

• Review of semiconductor fundamentals
  – Elementary quantum mechanics
  – Atomic bonding and crystal structures
  – Electronic band structures of solids

• Compound semiconductor materials
  – Compound semiconductor crystals
  – Material technologies

• Properties of heterostructures
  – Basic heterostructure properties
  – Electrical properties of heterostructures
  – Optical properties of heterostructures

• Heterostructure devices
  – High-speed electronic devices
  – Semiconductor lasers
  – New device development
Course Description (Detailed)

- Review of quantum, mechanical basics including wave-particle duality, Schröedinger wave equation, one-dimensional free and bounded particles in quantum wells
- Introduction to compound semiconductor crystals, structural and electrical properties, free carrier concentration and Fermi-Dirac integral, III-V alloys
- Phase equilibrium, growth of bulk crystals and phase equilibrium, liquid phase epitaxy, vapor phase epitaxy, metalorganic chemical vapor deposition, molecular beam epitaxy
- Basic heterostructure properties, energy band alignment models, strain effect on the bandgap energies, abrupt p-n heterojunction in equilibrium, heterojunction under bias
- Electronic properties of real quantum wells, potential barrier and tunneling, superlattices and miniband, quantum wells in electric fields, modulation doping and two-dimensional electron gas
- Optical properties of dielectrics, absorption, radiative transitions - Einstein relations, stimulated emission, absorption and emission rates in semiconductors, transitions in degenerated semiconductors, nonradiative recombination processes
- Metal-semiconductor field-effect transistors, pseudomorphic high-electron mobility transistors, heterojunction bipolar transistors, transfer electron devices, resonant tunneling devices
- Photodetectors, solar cells, light-emitting diodes (LEDs), dielectric waveguide and heterostructure laser theories, quantum well lasers, distributed feedback lasers, vertical cavity surface emitting lasers
Prerequisites

• ECE340 or equivalent basic semiconductor course
• Physics background – Basic modern physics
• Math background – differential equations
## Tentative Schedule [2]

<table>
<thead>
<tr>
<th>SEP 26: Doping and Deep Levels</th>
<th>SEP 28: The Fermi Integral, Free Carrier Concentration, Surface States</th>
<th>SEP 30: III-V Semiconductor Lattice Constant and Bandgap</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCT 3: III-N and Group IV Semiconductors</td>
<td>OCT 5: Crystal Growth, Phase Diagrams</td>
<td>OCT 7: Midterm Exam (Tentative)</td>
</tr>
<tr>
<td>OCT 10: Energy Band Alignment, Model-Solid Theory</td>
<td>OCT 12: Strained Layer Structures</td>
<td>OCT 14: Strain Effects on Band Edges</td>
</tr>
<tr>
<td>OCT 24: Realistic Finite Quantum Wells</td>
<td>OCT 26: Superlattices and Minibands</td>
<td>OCT 28: Heterostructures in Electric Fields and the Franz-Keldysh Effect</td>
</tr>
</tbody>
</table>

**Guideline Only: Subject to Change**
## Tentative Schedule [3]

<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCT 31:</td>
<td>Optical Properties of Dielectric Media</td>
</tr>
<tr>
<td>NOV 2:</td>
<td>Absorption in Semiconductors</td>
</tr>
<tr>
<td>NOV 4:</td>
<td>Transitions Between Discrete States</td>
</tr>
<tr>
<td>NOV 7:</td>
<td>Radiative and Non-Radiative Transitions Between Bands</td>
</tr>
<tr>
<td>NOV 9:</td>
<td>Introduction to Heterojunction Devices, MESFETs</td>
</tr>
<tr>
<td>NOV 11:</td>
<td>Modulation Doping</td>
</tr>
<tr>
<td>NOV 14:</td>
<td>High Electron Mobility Transistors (HEMTs)</td>
</tr>
<tr>
<td>NOV 16:</td>
<td>High Electron Mobility Transistors (HEMTs)</td>
</tr>
<tr>
<td>NOV 18:</td>
<td>GaN High Electron Mobility Transistors; NOV 21-25: Thanksgiving</td>
</tr>
<tr>
<td>NOV 28:</td>
<td>Heterojunction Bipolar Transistors (HBTs)</td>
</tr>
<tr>
<td>NOV 30:</td>
<td>Heterojunction Bipolar Transistors</td>
</tr>
<tr>
<td>DEC 2:</td>
<td>Heterostructure Lasers</td>
</tr>
<tr>
<td>DEC 5:</td>
<td>Heterostructure Lasers</td>
</tr>
<tr>
<td>DEC 7:</td>
<td>Photodiodes and Solar Cells; Last Lecture</td>
</tr>
<tr>
<td>FINAL EXAM:</td>
<td>Per Registrar’s Office</td>
</tr>
</tbody>
</table>

**Guideline Only: Subject to Change**
Grading and Policies
# Grading

<table>
<thead>
<tr>
<th>Grading Category</th>
<th>Percentage of Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homework &amp; Class Participation</td>
<td>30%</td>
</tr>
<tr>
<td>Quizzes (Dates Will be Announced)</td>
<td>10%</td>
</tr>
<tr>
<td>Mid-Term Exam</td>
<td>20%</td>
</tr>
<tr>
<td>Final Exam</td>
<td>40%</td>
</tr>
</tbody>
</table>

Homework:
- Due 1 week after assigned, due in class, no late homework accepted

Quizzes:
- 2 quizzes, dates will be announced ahead of time, 20 minutes

Exam(s):
- Calculator allowed
- 8.5 X 11, hand-written, double-sided formula sheet

Key Points:
- Come to class
- Do your homework
- If you’re having problems attend office hours
Other Comments

• Ask questions if you have them
• Don’t miss quizzes, exams, or homework
• Turn off your cell phones
• No video recording or photography in class
• Include name and NetID on all documents turned in for credit
• Class notes (required) can be purchased from the ECE Supply Center
• Additional reading materials will be distributed in class or through the course website
• Reference for further reading (NOT required):
  • Solid state physics:
  • Semiconductor physics and devices:
    – S.L. Chuang, *Physics of Semiconductor Devices*
  • Quantum wells and heterostructures:
  • Compound semiconductor materials: