ECE 488: Compound Semiconductors

M, W, F 11:00 – 11:50, 3013 ECEB
Professor John Dallesasse
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Office Hours: Tuesday 13:00 – 14:00
Lecture 21: October 12th, 2016
Assignments

• Reading from “Compound Semiconductors and Devices – An Introduction”
  – Wed 10/5: Chapter 5
  – Fri 10/7: None
  – Mon 10/10: §’s 6.1, 6.1.1, 6.1.2, 6.1.3, 6.1.4
  – Wed 10/12: §’s 6.2, 6.2.1, 6.2.2
  – Fri 9/14: §’s 6.3, 6.3.1, 6.3.2, 6.3.3, 6.3.4
• Homework: Posted 10/10, due 10/17
## Final Exam

<table>
<thead>
<tr>
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<td>7:00 PM</td>
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<td>3017 Electrical &amp; Computer Eng Bldg</td>
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Today’s Agenda

- Mobility
- Intentional Impurities
- The Fermi Integral
# 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>
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<tr>
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<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>
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<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>
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<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>
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**Guideline Only: Subject to Change**
Mobility

Continued
In Si, there are six equivalent conduction band minima in the first Brillouin zone. Electrons scattering between these valleys require large momentum change that involves optical phonons. This leads to an inter-valley scattering mobility:

\[ \mu_{iv} \propto \frac{1}{q^2} \left( \frac{m^*}{2} T \right)^{\frac{5}{2}} \left[ \exp \left( \frac{\hbar \omega_{op}}{kT} \right) - 1 \right] \]

where \( \hbar \omega_{op} \) is the optical phonon energy.

- **Polar scattering** (\( \mu_{po} \)):
  In compound semiconductors, the relative motion of neighboring different atoms will produce a net polarization in the direction of dilation. The induced electric field causes scattering and limits the mobility of electron. The scattering are mainly made with LO and TO phonons. It dominates the high temperature mobility of compound semiconductors.
Polar and Piezoelectric Scattering

\[ \mu_{po} \propto \begin{cases} \left( \frac{\varepsilon}{\varepsilon_0} - n^2 \right)^{-1} \left( m^* \right)^{3/2} \left( \frac{T}{\theta} \right)^{1/2} & \text{for } T > \theta_l \\ \left( \frac{\varepsilon}{\varepsilon_0} - n^2 \right)^{-1} \left( m^* \right)^{3/2} \left[ \exp \left( \frac{\theta_l}{T} \right) - 1 \right] & \text{for } T < \theta_l \end{cases} \]

\[ \theta_l = \frac{\hbar \omega_l}{k} \]

Equivalent temperature associated with LO phonons

Since the polar scattering mobility is inversely proportional to \((m^*)^{3/2}\), it leads to large difference in electron and hole mobility in III-V compounds.

**Piezoelectric scattering** \((\mu_{PE})\):

Piezoelectricity induced electric field can also interact with acoustic phonons. This is the **second most important scattering mechanism** in compound semiconductors other than \(\mu_{po}\).

\[ \mu_{PE} \propto \left( \frac{\varepsilon}{\varepsilon_0} \right) \left( \frac{m_0}{m^*} \right)^{3/2} T^{1/2} \]

This is the dominant scattering mechanism in II-VI compounds.
Alloy Scattering

- **Alloy scattering** ($\mu_{al}$):
  In the virtual crystal model, a homogeneous mixing of different atoms to form a ternary or quaternary alloy was assumed. The bond length of the alloy equals to the average value of the binary alloys. In close examinations, it turns out that the bond length of each constituent binary was not changed. Therefore, the alloy is NOT homogeneous but a mixture of “lumps” of binary alloys. Electrons moving through regions of different binary alloys will suffer “alloy” scattering. This scattering becomes important at high temperatures for ternary and quaternary alloys.

$$\mu_{Al} \propto \left( m^* \right)^{\frac{5}{2}} S^{-1} \Lambda \Delta u^{-2} T^{\frac{1}{2}}$$
Total Mobility

- **Total Mobility:**
  According to Matthiessen’s rule, the total mobility is calculated as the inverse sum of each individual mobility components.

\[
\frac{1}{\mu_{\text{total}}} = \sum \frac{1}{\mu_i} = \frac{1}{\mu_n} + \frac{1}{\mu_i} + \frac{1}{\mu_{\text{iv}}} + \frac{1}{\mu_{\text{po}}} + \frac{1}{\mu_{\text{PE}}} + \frac{1}{\mu_{\text{Al}}}
\]
Doping and Impurities
Intentional Impurities

**Intentional Shallow Impurities**

- III-V compounds doped with group-II impurity:
  Dopants will substitute group-III elements and show $p$-type conductivity.
- III-V compounds doped with group-VI impurity:
  Dopants will substitute group-V elements and show $n$-type conductivity.
- Amphoteric doping by adding group-IV elements into III-V compounds:
  The electric conductivity depends on the type of substituting sites. When substituting group-III and group-V elements, the material conductivity becomes $n$-type and $p$-type, respectively.

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Activation Energy (Ionization Energy)

The energy required to ionize a dopant (release an electron in n-type material and capture an electron in p-type semiconductor) is called the “activation energy”.

For simple shallow impurities, the activation energy can be estimated from the Coulomb interaction between the impurity atom and the attached charge carrier. This is similar to the hydrogen atom with one electron attached. Bohr radius $a_B$ defines the trajectory where the bonded electron is most likely located.

- Donors:
  The ionization energy for a hydrogen atom is
  \[
  E_n = \left[ \frac{m_0 e^4}{2(4\pi\epsilon_0 \hbar)^2} \right] \frac{1}{n^2} = \frac{R_y}{n^2} = \frac{13.6}{n^2} \text{(eV)}
  \]

  When applying this model to shallow donors, the effective mass of the semiconductor $m^*$ is used for free electron mass $m_0$. The dielectric constant of the semiconductor $\epsilon_r \epsilon_0$ will replace the free space value $\epsilon_0$. 
Donor Activation Energy and Radius

\[ E_d = \left[ \frac{m^* e^4}{2(4\pi \varepsilon_o \varepsilon_r \hbar^2)} \right] \frac{1}{n^2} = \left[ \frac{m^*/m_o}{(\varepsilon_o \varepsilon_r / \varepsilon_o)^2} \right] R_y = 13.6 \left( \frac{m^*/m_o}{\varepsilon_r^2} \right) (eV) \ll E_1 \]

The donor Bohr radius becomes

\[ a_B^* = \frac{4\pi \varepsilon_o \varepsilon_r \hbar^2}{m^* e^2} = 0.53 \left( \frac{\varepsilon_r}{m^*/m_o} \right) (\text{Å}) \gg a_B \]

For GaAs, \( m^* = 0.067 m_o \) and \( \varepsilon_r = 13.1 \), the calculated activation energy is \( E_d = 5.3 \text{meV} \) and \( a_B^* = 103 \text{Å} \).

- Since \( E_d << kT (\sim 26 \text{meV}) \) at room temperature, all shallow impurities are considered fully ionized at room temperature.
- Also, \( a_B^* \gg a \) (lattice constant, \( a = 5.653 \text{Å} \) for GaAs), the electron associated with the impurity has a wave function extending much larger than the unit cell.
Acceptor Activation Energy

- Acceptors:
  
  Since the degeneracy of light hole band and heavy hole band near the zone center of the valence band, the simple hydrogen model approach used to calculate $E_a$ is not applicable for acceptors. 

  In the limit of $E_a \ll \Delta$ (split-off energy), the activation energy of acceptors is calculated using a sophisticated quantum mechanical model. The results are shown below. [Baldareschi and Lipari, Phys. Rev. B8, 2697 (1973)]

  $$E_a = R_y f(\mu); \quad \mu = \frac{4\gamma_2 + 6\gamma_3}{5\gamma_1}; \quad R_y = \left[ \frac{m_h^* e^4}{2(4\pi\varepsilon\hbar)^2} \right] \frac{1}{\gamma_1}; \quad a_B^* = \left( \frac{4\pi\varepsilon\hbar^2}{m_h^* e^2} \right) \gamma_1$$

  where $\gamma_1$, $\gamma_2$ and $\gamma_3$ are the Luttinger parameters which describe the hole dispersion relationships near the zone center.

<table>
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<th>III-V</th>
<th>AlSb</th>
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<th>GaAs</th>
<th>GaSb</th>
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<th>InSb</th>
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<td>12.5</td>
<td>35.3</td>
<td>16.6</td>
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- General doping characteristics:
  - **Type of valence electron** determines the doping type ($n$- or $p$-type);
  - The atomic **size** of dopant determines the maximum doping concentration and diffusion property;
  - The **vapor pressure** of the dopant affects the stability and control of the doping process.
Group II Dopants

Group-II impurities incorporated on the anion (group-III) sites of III-V compounds form shallow acceptors.

- **Be:**
  - $E_a(GaAs) = 28 \text{ meV}$, $E_a(InP) = 41 \text{ meV}$.
  - Diffusion slowly. $D = D_0 \exp(-E_0/kT)$; $E_0 = 1.95 \text{ eV}$, $D_0 = 2 \times 10^{-5} \text{ cm}^2$.
  - Used in MBE growth, ion implantation, ohmic contacts.

- **Zn:**
  - $E_a(GaAs) = 31 \text{ meV}$, $E_a(InP) = 47 \text{ meV}$.
  - High diffusion coefficient.
  - Widely used in MOCVD and ohmic contacts. Due to the high vapor pressure, it’s not suitable for MBE growth.

- **Mg:**
  - $E_a(GaAs) = 28 \text{ meV}$, $E_a(InP) = 41 \text{ meV}$.
  - High affinity to oxygen to form MgO.
  - Used in nitride compounds.

- **Cd:**
  - $E_a(GaAs) = 35 \text{ meV}$, $E_a(InP) = 56 \text{ meV}$.
  - Highest vapor pressure among all (two order of magnitudes higher than Zn).
Group VI Dopants

Group-VI impurities incorporated on the cation (group-V) sites of III-V compounds form shallow donors.  

- **S:**
  - $E_a(GaAs) = 6\ meV$.
  - Very high vapor pressure.
  - $H_2S$ is commonly used as the $S$ doping source in CVD.

- **Se:**
  - $E_a(GaAs) = 6\ meV$.
  - Similar to $S$ but with strong memory effect.
  - $H_2Se$ is commonly used as the $Se$ doping source.

- **Te:**
  - $E_a(GaAs) = 30\ meV$. The much higher activation energy is due to the large atomic size of $Te$.
  - Diethyltellurium [$(C_2H_5)_2Te,\ DETe$] has been used as Te doping precursor for MOCVD growth of GaAs and InP.
Group IV Dopants

- Attributes of group-IV impurities in III-V compounds:
  - They are *amphoteric* so that they can occupy either group-III or group-V sites to become donors or acceptors, respectively.
  - They *autocompensate* at high doping levels.
  - *Saturation* of activation of impurities at high doping levels.
  - *Doping condition dependent* electrical properties.

- **C:**
  - $E_d(GaAs) = 26 \text{ meV}$, $E_d(InP) = 43 \text{ meV}$.
  - Very low diffusion rate and can achieve high doping level ($> 10^{20} \text{ cm}^{-3}$).
  - $CCl_4$ and $CBr_4$ are commonly used C source.

- **Si:**
  - $E_d \sim 4-6 \text{ meV}$ in most III-V compounds at $< 2 \times 10^{18} \text{ cm}^{-3}$.
  - Strongly compensates at $> 5 \times 10^{18} \text{ cm}^{-3}$.
  - Solid Si source for MBE and ion implantation.
  - $SiH_4$ and $Si_2H_6$ are used in MOCVD.

- **Ge:**
  - Strongly amphoteric in III-V compounds.
  - Au-Ge alloy is a common $n$-type ohmic contact metal.

- **Sn:**
  - A shallow donor impurity (4-6 meV).
  - Severe surface segregation problem.
Among Be, C, and Si, carbon has the lowest diffusion coefficient.

The doping type and concentration in GaAs:Si grown by liquid-phase epitaxy depend on the growth temperature as well as impurity concentration.
Hydrogen Passivation

The hydrogen atom with one valence electron can easily bond to an impurity or a complex site covalently and totally masking the doping effect. The hydrogen passivation works for both donor and acceptor impurities. This process is specially severe during growth process using hydrogen containing sources such as in MOCVD.

Using silicon doped GaAs as an example:
- Under normal condition, a Si atom will replace a Ga and bounds with four nearest neighboring As atoms. An extra electron is presented as the donor electron.
Hydrogen Donor Passivation

- **Donor passivation:**
  A hydrogen can bound to Si donor during the doping process. The small hydrogen atom can fit in an interstitial site such that the Si donor atom has no bond left to bound the As atom on the opposite site. This As will have three covalent bonds and a pair of lone electrons. The Si-H complex yields a neutral electron count. Thus, the Si donor is passivated by the hydrogen atom. Other doping impurities passivated by hydrogen are Ge, Sn, Se, and Te.

- The donor-hydrogen bond can be dissociated by thermal annealing at relatively low temperature of ≥400°C. The doping concentration will be mostly recovered after thermal annealing.
Hydrogen Acceptor Passivation

- **Acceptor passivation:** When a group-II dopant replaces a Ga atom, it can also be passivated by a hydrogen atom. The hydrogen atom is bound to an As atom between the acceptor atom and the As atom. The hydrogen atom satisfies the electron pairing requirement of the As neighbor and detached from the acceptor atom. The extra bonding electron from the detached As atom is transferred to the group-II acceptor bonding to three neighboring As atoms. Therefore, the entire H-acceptor complex is neutral. Again, the acceptor-hydrogen bond can be dissociated by thermal annealing.
Agenda for Next Class

• Deep Levels
• Fermi Integral
• Multiple Valleys
• Surface States
• Charge Neutrality Level
Thank You!
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.
Common Semiconductors

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

“Italic” = indirect gap
“Roman” = direct gap
☐ hexagonal structure
☐ cubic structure

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E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org
Contact Information & Website

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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, Schroedinger 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 [1]

<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
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<th>Date</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUG 22</td>
<td>Introductions, Objectives, Class Outline, Policies</td>
<td>AUG 24</td>
<td>Motivation, Intro to Quantum Theory</td>
<td>AUG 26</td>
<td>Infinite Square &amp; Triangle Wells</td>
</tr>
<tr>
<td>AUG 29</td>
<td>Potential Steps, Coulomb Well (Hydrogen Atom), Atomic Bonding</td>
<td>AUG 31</td>
<td>Crystal Structures, Diffraction</td>
<td>SEP 2</td>
<td>Reciprocal Space, Diffraction Condition</td>
</tr>
<tr>
<td>SEP 5</td>
<td>LABOR DAY NO CLASS</td>
<td>SEP 7</td>
<td>The Brillouin Zone, Band Structures, Density of States</td>
<td>SEP 9</td>
<td>Bloch Theorem, Empty Lattice Model</td>
</tr>
<tr>
<td>SEP 12</td>
<td>Band Gaps</td>
<td>SEP 14</td>
<td>Kronig-Penny Model</td>
<td>SEP 16</td>
<td>Effective Mass, Bloch Oscillations, Band Structure</td>
</tr>
<tr>
<td>SEP 19</td>
<td>Compound Semiconductor Crystals</td>
<td>SEP 21</td>
<td>Phonons</td>
<td>SEP 23</td>
<td>Electrical Properties, Gap, Effective Mass, Mobility</td>
</tr>
</tbody>
</table>

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