ECE 488: Compound Semiconductors

M,W,F 11:00 – 11:50, 3013 ECEB
Professor John Dallesasse
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E-mail: jdallesa@illinois.edu
Office Hours: Tuesday 13:00 – 14:00
Lecture 37: November 18th, 2016
Assignments

• Reading from “Compound Semiconductors and Devices – An Introduction”
  – Mon 11/14: §’s 9.4, 9.5, 9.5.1, 9.5.2, 9.5.3
  – Wed 11/16: §’s 9.5.4, 9.6, 9.6.1, 9.6.2
  – Fri 11/18: §’s 9.7, 9.7.1, 9.7.2, 9.7.3

• Homework: Posted Friday 11-11, Due 11-18

• Next Homework: Posted Friday 11-18, Due Monday 12-5
Today’s Agenda

• Optical Properties of Compound Semiconductors: Dielectric Constant, Refractive Index, and Absorption
• Absorption in Semiconductors
• Indirect Transitions
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**Guideline Only: Subject to Change**
Optical Properties of Compound Semiconductor Heterostructures

Absorption
Absorption in Semiconductors

Reststrahlen Absorption – Due to phonons
Absorption Coefficient

The absorption coefficient is defined as the fraction of the power loss \( \frac{dI}{I} \) per unit length, where \( I \) is the optical power.

\[
\alpha(hv) = \frac{\frac{dI}{I}}{dz} \quad (cm^{-1})
\]

The calculation of \( \alpha \) in a semiconductor involves detailed knowledge of the transition probability of electrons \( W_{if} \) between valence and conduction bands for each energy, and the available electron filled initial states \( n_i \) in the valence band and the empty final states \( n_f \) in the conduction band.

\[
\alpha(hv) = A \sum W_{if} n_i n_f
\]

When evaluating the transition probability at any wave vector \( \mathbf{k} \), in order to fulfill the momentum conservation condition, we need to consider DOS jointly both in the conduction and valence bands.
Allowed Direct Band-to-Band Transitions

This type of optical transition requires that the system must fulfill both the momentum conservation \((k_i = k_f)\) and energy conservation \((\hbar \nu = E_f - E_i)\) conditions. Therefore, this type of transition only applies to direct band gap semiconductors. We will examine the absorption coefficient of an optical excitation \(\hbar \nu\) between \(E_i\) in the valence band and \(E_f\) in the conduction band at the same wave vector \(k\). The top of the valence band is set equal to zero energy.

Assuming a parabolic band structure,

\[
\begin{align*}
E_f &= E_g + \frac{\hbar^2 k^2}{2m_e^*} \\
E_i &= -\frac{\hbar^2 k^2}{2m_h^*}
\end{align*}
\]

\[
\hbar \nu = E_f - E_i = E_g + \frac{\hbar^2 k^2}{2} \left( \frac{1}{m_e^*} + \frac{1}{m_h^*} \right)
\]

\[
\therefore \quad \hbar \nu = E_g + \frac{\hbar^2 k^2}{2m_r}
\]

\[
\Rightarrow \quad k = \sqrt{\frac{2(\hbar \nu - E_g)m_r}{\hbar}}
\]
Following a similar procedure, the joint DOS is calculated as

\[ D(hv) = \frac{(2m_r)^{3/2}}{2\pi^2h^3} \sqrt{hv - E_g} \]

The transition probability derived from the first order, time-independent perturbation theory is

\[ W_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 D(hv) \]

\( M_{if} \) is the matrix element of the perturbation which connects the states \( i \) and \( f \) of the system. \( M_{if} \) is independent of \( k \). Therefore, the absorption coefficient for allowed direct-transitions is

\[ \alpha(hv) = A^*(hv - E_g)^{1/2} \]

where \( A^* \) is a constant and has a value of \( \sim 10^4 \) for GaAs. \( \alpha^2 \) has a straight line relation with energy and has a zero value at \( E = E_g \).
All direct band gap semiconductors show rapid increase of $\alpha$ with increasing energy. The increasing of $\alpha$ in indirect band gap semiconductors is slower. However, the rapid increase of $\alpha$ in Ge near 0.8 eV indicates the onset of the direct transition.
Indirect Transitions
Indirect Transitions

To fulfill the momentum and energy conservation conditions simultaneously, absorption or emission of phonons during the transition process is required.

\[
\begin{align*}
\hbar v_a &= E_f - E_i - \hbar \omega_p \quad \text{(phonon absorption)} \\
\hbar v_e &= E_f - E_i + \hbar \omega_p \quad \text{(phonon emission)}
\end{align*}
\]

Assume the total allowed energy interval between \( E_f \) and \( E_i \) is \( \delta \).

\[
\delta = (E_f - E_c) + (E_v - E_i) = E_f - E_g - E_i
\]

or

\[
\delta = \hbar \nu - E_g \pm \hbar \omega_p
\]

The DOS of the final states in the conduction band and DOS of the initial states in the valence band are

\[
D(E_f) = A_c \sqrt{E_f - E_c} = A_c \sqrt{\delta - E_i}
\]

\[
D(E_i) = A_v \sqrt{E_v - E_i} = A_v \sqrt{E_i}
\]

In the last term of both equations, we used the absolute value of \( E_i \).
Phonon Absorption

The effective DOS for the transitions is

\[ D(h\nu) \propto \int_0^\delta D(E_f) D(E_i) dE_i = A_c A_v \int_0^\delta \sqrt{\delta - E_i} \sqrt{E_i} dE_i = A_c A_v \delta^2 \]

\[ D(h\nu) \equiv A_a \delta^2 = A_a \left( h\nu - E_g \pm \hbar \omega_p \right)^2 \]

Since the absorption depends on phonon absorption/emission processes, the probability of phonon absorption \((-\hbar \omega_p)/\text{emission } (+\hbar \omega_p)\) should be included. The **phonon absorption** probability is proportional to the phonon density, which has a Bose-Einstein distribution (ignoring the Pauli exclusion principle), shown below.

\[ N(\hbar \omega_p) = \left( \exp \left( \frac{\hbar \omega_p}{kT} \right) - 1 \right)^{-1} \]

The absorption coefficient due to indirect transitions involving phonon absorption becomes

\[ \alpha_a = \frac{A_a \left( h\nu - E_g + \hbar \omega_p \right)^2}{\exp \left( \hbar \omega_p / kT \right) - 1} \]

Since \(\hbar \omega_p > kT, N(\hbar \omega_p) < 1\).

- At \(\alpha_a = 0, h\nu = E_g - \hbar \omega_p\)
- \(\sqrt{\alpha_a} \propto h\nu = E\)
Phonon Emission

For the absorption process involving phonon emissions, the phonon emission probability is the sum of stimulated emission probability (equal to absorption) and spontaneous emission probability (unity) and equals

\[ N(\hbar \omega_p) + 1 = \left[ 1 - \exp \left( -\frac{\hbar \omega_p}{kT} \right) \right]^{-1} \]

The absorption coefficient due to indirect transitions involving phonon emission has the form of

\[ \alpha_e = \frac{A_a (h \nu - E_g - \hbar \omega_p)^2}{1 - \exp \left( -\hbar \omega_p / kT \right)} \]

At \( \alpha_e = 0, h \nu = E_g + \hbar \omega_p \). The total absorption is the sum of the two processes.

\[ \alpha = \alpha_a + \alpha_e \]

At very low temperatures, there are very few phonons available for absorption and \( \alpha_a \) diminishes.
Both Ge and Si show square root absorption dependence on energy;
- Phonon emission and absorption processes are clearly shown;
- At low temperature, absorption involving phonon absorption ($\alpha_a$) diminished.
8.2.3. Exciton Absorption:

- Exciton is a bound electron-hole pair formed by the mutual Coulomb attraction force.
- The electron moves around the hole as if a hydrogen-like atom with a reduced mass \( m_r \).

\[
\frac{1}{m_r} = \frac{1}{m_e^*} + \frac{1}{m_h^*}
\]

The hydrogen atom-like exciton has a reduced binding energy due to the reduced mass and larger dielectric constant.

\[
E_x = -\left( \frac{m_r e^4}{2\hbar^2 \varepsilon^2} \right) \frac{1}{n^2} = -\frac{m_r}{m_o \varepsilon_r} \frac{R_y}{n^2}
\]

\( R_y = 13.6eV \) and \( n \) is an integer.
- \( E_x \) has many values below the conduction band edge \( (n \geq 1) \).
- For \( n \to \infty \), \( E_x = 0 \) or \( E_c - E_x = 0 \).
- For \( n = 1 \), in GaAs, using \( m_r = 0.059m_o \) and \( \varepsilon_r = 13.2 \), we obtained an \( E_x = -4.6meV \). The small binding energy makes it be dissociated at room temperature easily and cannot be observed.
In direct band gap materials, free excitons exist just below the band edge where \( E = E_g - E_x \). Due to the much lighter reduced mass compared with that of the proton in a hydrogen, the moving exciton has a much higher kinetic energy. Thus, the exciton levels are slightly broadened into bands.

The free electrons and holes having the same momentum \( k \) are, in general, moving with different velocities: \( h(dE_c/dk) \) for electrons and \( h(dE_v/dk) \) for holes. Since the \( e-h \) pair (EHP) must move together in an exciton, their translational velocities must be identical.

\[
\frac{dE_c}{dk} = \frac{dE_v}{dk}
\]

Therefore, only in certain regions of the \( E-k \) curve does exciton exist. The most likely place to find excitons are near ‘critical points’ of \( \Gamma, L, \) and \( X \).
Exciton dissociation is clearly seen in the sample measured near room temperature;
At low temperature, the exciton peak helps in determining the energy band gap.
Bound exciton complex:
An electron bound to the donor form a ‘neutral donor’. A free hole can combine with such a ‘neutral donor’ to form a positive charged complex called ‘donor bound exciton’. The electron travels in a wide orbit about the ‘fixed’ donor while the associated hole moves in the electrostatic field of the $e^- - h^+$ dipole. The instantaneous position of the hole is determined by the electron and the field.

An electron associated with a neutral acceptor is also a bound exciton.
Excitons in indirect band gap semiconductors:
In indirect band gap semiconductors, excitons are formed with the simultaneous absorption/emission of phonons. The transition occurs at

\[ h\nu = E_g - E_x \pm \hbar \omega_p \]

✓ The additional momentum acquired from phonons made the exciton level broadened into bands.

✓ Instead of absorption peak, steps will appear in exciton absorption spectra. This is because the phonons allow connecting states with the same velocity $dE/dk$ at photon energies greater than those connecting the band-edge excitons.

✓ More than one phonon ($TA_e, TA_a, TO_e, TO_a, LA_e, LA_a,$ and $LO_e, LO_a$) can participate in the transition. This cause a large number of steps in the absorption edge to be detected.

Therefore, the absorption spectrum of the indirect band gap material has a complex shape with many absorption steps originated from different phonon absorption processes.
Excitons dissociated at high temperature and show weak steps;
More pronounced steps are seen at low temperature;
Phonon absorption dominated at high temperature and phonon emission is the major absorption process at low temperature.
Excitons in Quantum Wells

- Excitons in quantum wells (QW): Due to the large overlap of electron and hole wave functions inside a QW, the exciton binding energy is enhanced. The 2D exciton binding energy can be calculated by solving the 2D Schrödinger equation of a hydrogen model.

\[
E_x^{2D} = -\frac{m_r e^4}{2\hbar^2 e^2} \frac{1}{(n - \frac{1}{2})^2} = -\left(\frac{m_r}{m_0 e^2}\right) R_y \left(n - \frac{1}{2}\right)^2
\]

The exciton binding energy in QW is reduced. In GaAs QW, \(E_x^{2D} = 4E_x^{3D}\). Due to the large binding energy, the excitonic effect could be observed even at room temperature!
Excitons in Quantum Wells (2)

- First observation of exciton absorption in QW:
  Using MBE, GaAs/Al_{0.2}Ga_{0.8}As QW was first demonstrated by Ray Dingle at Bell Labs in 1974. (R. Dingle, W. Wiegmann, and C. H. Henry, Phys. Rev. Lett., 33, 847 (1974)) The samples were measured at 2K. A pronounced exciton peak was observed in bulk GaAs. The QW absorption steps are clearly shown with associated exciton peak. The calculated absorption levels are shown on the right. However, the parameters used for calculation were inaccurate.
Agenda for Next Class

- Isoelectronic Traps
- Radiative Transitions
Thank You!
# Final Exam

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### Periodic Table of the Elements

#### Table Contents:
- **Magnesium (Mg)**: Atomic Symbol: Mg, Atomic Number: 12, Atomic Mass: 24.305, Group II, Period 3, Family of Alkaline Earth Metals.

#### Elements by Group:
- **Group I (Alkaline Metals)**: Includes Hydrogen (H), Lithium (Li), Sodium (Na), Potassium (K), Rubidium (Rb), Cesium (Cs), and Francium (Fr).
- **Group II (Alkaline Earth Metals)**: Includes Beryllium (Be), Magnesium (Mg), Calcium (Ca), Strontium (Sr), Barium (Ba), and Radon (Rn).
- **Group III (Aldrin Metals)**: Includes Aluminum (Al), Gallium (Ga), Indium (In), Thallium (Tl), and Lead (Pb).
- **Group IV (Group IV - Carbon and Silicon)**: Includes Carbon (C), Silicon (Si), Germanium (Ge), Tin (Sn), and Lead (Pb).
- **Group V (Group V - Nitrogen and Phosphorus)**: Includes Nitrogen (N), Phosphorus (P), Arsenic (As), Antimony (Sb), and Bismuth (Bi).
- **Group VI (Group VI - Oxygen and Sulfur)**: Includes Oxygen (O), Sulfur (S), Selenium (Se), Tellurium (Te), and Polonium (Po).
- **Group VII (Group VII - Fluorine and Chlorine)**: Includes Fluorine (F), Chlorine (Cl), Bromine (Br), Iodine (I), and Astatine (At).
- **Group VIII (Group VIII - Iron and Nickel)**: Includes Iron (Fe), Nickel (Ni), Cobalt (Co), and Platinum (Pt).
- **Group IX (Group IX - Copper and Silver)**: Includes Copper (Cu), Silver (Ag), and Mercury (Hg).
- **Group X (Group X - Gold and Mercury)**: Includes Gold (Au), Mercury (Hg), and Thallium (Tl).
- **Group XI (Group XI - Rhenium and Osmium)**: Includes Rhenium (Re), Osmium (Os), and Ruthenium (Ru).
- **Group XII (Group XII - Iridium and Palladium)**: Includes Iridium (Ir), Palladium (Pd), and Platinum (Pt).
- **Group XIII (Group XIII - Indium and Tin)**: Includes Indium (In), Tin (Sn), and Lead (Pb).
- **Group XIV (Group XIV - Antimony and Tellurium)**: Includes Antimony (Sb), Tellurium (Te), and Polonium (Po).
- **Group XV (Group XV - Arsenic and Selenium)**: Includes Arsenic (As), Selenium (Se), and Tellurium (Te).
- **Group XVI (Group XVI - Bismuth and Polonium)**: Includes Bismuth (Bi), Polonium (Po), and Astatine (At).
- **Group XVII (Group XVII - Bromine and Iodine)**: Includes Bromine (Br), Iodine (I), and Astatine (At).
- **Group XVIII (Group XVIII - Oxygen and Chlorine)**: Includes Oxygen (O), Chlorine (Cl), and Bromine (Br).

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

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Common Semiconductors

“Italicics” = indirect gap
“Roman” = direct gap

hexagonal structure
cubic structure

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

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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, Schrödinger 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]

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**Guideline Only: Subject to Change**
## Tentative Schedule [2]

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<td>OCT 28: Heterostructures in Electric Fields and the Franz-Keldysh Effect</td>
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**Guideline Only: Subject to Change**
Grading and Policies
# Grading

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<td>Final Exam</td>
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**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: