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 23: October 17th, 2016
Assignments

• Reading from “Compound Semiconductors and Devices – An Introduction”
  – 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 10/14: §’s 6.3, 6.3.1, 6.3.2, 6.3.3, 6.3.4
  – Mon 10/17: §’s 6.4, 6.5, 6.5.1, 6.5.2, 6.5.3, 6.5.4
  – Wed 10/19: §’s 7.1, 7.1.1, 7.1.2
  – Fri 10/21: §’s 7.2, 7.2.1, 7.2.2

• Homework: Will be assigned Wed or Fri, due 1 week after
Today’s Agenda

- Doping Effects (Continued)
- Deep Levels
- Surface States and the Charge Neutrality Level (CNL)
## Tentative Schedule [2]

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<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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<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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<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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</table>

**Guideline Only: Subject to Change**
Doping Effects

Continued
4.4.3. Carrier concentration in multiple valley Limits:

If the energy difference between conduction band minima along different directions is small, the electron distribution is not limited to the lowest band. Depending on the energy separation between $E_F$ and the conduction band minimum in $\Gamma, L, \text{and } X$ direction, the electron distribution in each valley can be calculated.

Let $\eta_i = \frac{E_F - E_C^i}{kT}$ where $i = \Gamma, L, \text{and } X$ valley

In degenerate semiconductor,

$$n = N_C^\Gamma F_{1/2}(\eta_\Gamma) + N_C^L F_{1/2}(\eta_L) + N_C^X F_{1/2}(\eta_X)$$

$$N_C^i = \frac{2\pi m_e^* kT}{\hbar^2}^{3/2} = 2.5 \times 10^{19} \left( \frac{m_e^*}{m_o} \right)^{3/2} \left( \frac{T}{300} \right) (cm^{-3})$$

In non-degenerate semiconductor, the electron distribution equation can be simplified using Boltzmann approximation.

$$n = N_C^\Gamma \exp(\eta_\Gamma) + N_C^L \exp(\eta_L) + N_C^X \exp(\eta_X)$$
Burstein-Moss Shift

- Burstein-Moss shift (Band Filling):
  Due to the small DOS in the conduction band of \( n \)-type compound semiconductors, the Fermi level can easily merge into the conduction band at high doping level. The absorption transitions in highly doped \( n \)-type semiconductor will take place between the top of the valence band and \( E_F > E_C \). The transition energy will be larger than the band gap energy since all states below the Fermi level are full.
Impurity Bands and Band Tails:

At low doping concentration, the impurity states are well defined. The carrier transport process is through hopping conduction. As the impurity concentration increases with random distribution, overlapping impurity states form an *impurity band*. At still higher impurity concentrations, the impurity band widens and merges with the conduction band. The transport process is the impurity band conduction.

The conduction bandwidth ($\Delta E_D$) in GaAs doped at a level of $>10^{16} \text{cm}^{-3}$ is less than 2.5 meV.
The band edge is also modified by random distribution of impurity charges which leads to potential fluctuations of the band edges. In an undoped semiconductor, such fluctuations are absent and the band edges are well defined. In a highly doped semiconductor, the impurity induced potential fluctuations cause the band edges to vary spatially. States with energy below the unperturbed conduction band edge or above the unperturbed valence band edge are called the tail states. The tail states significantly change the DOS in the vicinity of the band edge.
Bandgap Narrowing

At high doping concentrations, the bandgap energy of semiconductors decreases. This is referred to as bandgap narrowing, bandgap shrinkage, or bandgap renormalization. In addition to the formation of band tails and impurity bands, the many-body effects of free carriers are the other important reasons of bandgap narrowing.

All the carrier-carrier and carrier-impurity interactions, including electron-electron, electron-donor, hole-hole, hole-acceptor, and electron-hole interactions, tend to lower the total energy and lead to a decrease in gap energy.

- In $n$-type semiconductor, the bandgap narrowing causes the Fermi level to decrease, while the Burstein-Moss shift is due to an increase of the Fermi level. In GaAs, the Burstein-Moss shift prevails, resulting in a blue-shift of the absorption edge.

- In $p$-type GaAs, the bandgap narrowing prevails and results in a red-shift of the absorption edge.
Bandgap Narrowing

- n-type GaAs
  - $T = 297$ K
  - $n = 5.9 \times 10^{17} \text{cm}^{-3}$
  - 2 x $10^{18}$
  - 6.7 x $10^{18}$
  - 3.3 x $10^{18}$

- p-type GaAs
  - $p = 4.9 \times 10^{17} \text{cm}^{-3}$
  - 2.2 x $10^{17}$
  - 1.6 x $10^{19}$
  - 1.2 x $10^{18}$
  - 2.4 x $10^{18}$

Absorption coefficient $\alpha$ (cm$^{-1}$) vs. Energy $E$ (eV)
Deep Levels
Donor Complex (DX) Centers

$n$-type $Al_xGa_{1-x}As$ with $Al$ mole fraction of $0.2 \leq x \leq 0.4$ has many unusual properties including

- Large donor activation energy ($\geq 130 \text{meV}$);
- Light sensitive conductivity on optical radiation; and
- Large barrier to emission and capture carriers.

These anomalous properties are not expected from a hydrogen-like donor. It was speculated that the deep center involves a donor atom which forms a complex with another constituent. The center was designated as the donor-complex or DX-center.

The existing of DX-centers in $n$-type $Al_xGa_{1-x}As$ results a persistent photo-conductivity (PPC) effect which makes the control of electron concentration unpredictable and degrades the performance of GaAs-AlGaAs high electron mobility transistors.
Persistent Photoconductivity (PPC) Effect

- Upon illumination of an $n$-type $Al_{0.32}Ga_{0.68}As$ at low temperature, the carrier concentration increases.
- The light used for illumination has a wavelength below the bandgap of $Al_{0.32}Ga_{0.68}As$.
- The increase in carrier concentration persists for hours to days even after the light has been turned off.
- Very large donor activation energy, $E_{dd} = 135 \text{meV}$, was observed. This large $E_{dd}$ is obtained only if a DOS much larger than that of $\Gamma$ valley is used.
- Conventional model did not offer a good match to experimental data.
DX Centers

\[ D^0 + e = DX^- \]

\[ D^+ + 2e = DX^- \]
The EL2 defect center is instrumental in rendering semi-insulating nominally undoped GaAs bulk crystal grown by the liquid-encapsulated Czochralski (LEC) technique. The EL2 center, as revealed in the deep level transient spectroscopy (DLTS) spectrum, shows a major signal at $T = 390K$, which corresponding to an activation energy of $\sim 0.74\,eV$ below the conduction band.
The EL2-center in GaAs has been identified to be the As-antisite defect, \( As_{Ga} \), i.e., a native defect with no other constituent. Since As has two excess electrons if occupying a Ga site, the As antisite defect becomes a double donor.

In bulk GaAs, the dominant residual impurity is carbon, a shallow acceptor, with a concentration in the \( 10^{15} cm^{-3} \) range.

Adding sufficient amount of EL2 centers, a fraction of the EL2 centers will be ionized to compensate C shallow acceptors and the remaining EL2 centers will stay neutral. This is because the ionization energy of 0.75\( eV \) is too large for a thermal ionization process at room temperature. (The electron loses energy to fill a hole state.)

As a consequence, the Fermi level is pinned at the EL2 level which is approximately in the middle of the GaAs band gap (1.43\( eV \)). Thus, the GaAs bulk crystal with sufficiently high concentration of EL2 centers shows near intrinsic characteristics.
EL2-Related Transitions

- The configuration of the $As_{Ga}$ antisite defect has a strong similarity to the DX center. If the As atom takes the substitution site of Ga, the normal antisite defect is formed. The $As_{Ga}$ is about 0.9Å above the tetrahedron base plane. This state corresponds to a donor level of 0.75eV below $E_C$.
- If the As atom takes the interstitial site as Si in the DX center, the $As_{Ga}$ is approximately 0.3Å below the plane of three As neighbors. This metastable state has an energy level above the normal state.
- The As atom moves 1.2Å along the <111> direction associated with the configuration change and breaks one of its bonds.
- The normal-to-metastable transition is a neutral-to-neutral state transition.
Controlling EL2 Center Concentration

- The concentration of EL2 centers can be controlled during the LEC growth of GaAs bulk crystal via the As/Ga composition ratio in the melt. At the stochiometric condition, As:Ga=1.
- For As concentration above 47.5%, the GaAs becomes semi-insulating with resistivity $\rho > 10^7 \Omega \cdot cm$. For an As concentration below 47.5%, $p$-type GaAs will form.
Surface States
For an ideal metal-semiconductor interface, the Schottky barrier height is

\[ \phi_b = \phi_m - \chi_s \]

where \( \phi_m \) is the metal work function and \( \chi_s \) is the semiconductor electron affinity.

The Schottky barrier height is expected as a function of the metal work function using different metals. In reality, \( \phi_b \) does not follow this prediction. For example, the barrier height of GaAs has a nearly constant value and independent of the metal used.
Surface States

It was pointed out at the early stage of semiconductor technology development by John Bardeen that the “surface states” play an important role in the physical properties of carrier transport near the semiconductor surface. The surface defects and surface contaminations cause a surface space charge layer, which can “pin” the Fermi level near the middle of the bandgap - Bardeen limit.

The measured $\phi_b$ is “pinned” at a fixed value and independent of the metal used. This situation is more severe for compound semiconductors than Si, due to the more complex surface structure.
Surface Reconstruction

- Surface pinning mechanism:
  
  On cleaved (100) and (111) surfaces, the surface atoms do not retain their idea bulk structures but undergo a surface reconstruction. The surface reconstruction allows surface atoms take a different periodic arrangement to minimize energy.

  For III-V compounds, the (110) surface is the easy cleave plane. The (110) surface is a non-polar surface and can be studied through in-situ cleavage in vacuum. On (110) cleaved plane, the surface atoms take a relaxed configuration. The As covalent bond (1.18Å) moves outward and the Ga bond (1.26Å) moves inward on the surface after bonds are broken from the surface. To minimize the energy, the As and Ga surface atoms will take their isolated atomic $s^2p^3$ and $s^2p^1$ configurations, respectively, rather than the bulk $s^1p^3$ configuration. Note, the $s^2p^1$ configuration has a more planar bond arrangement than the $s^1p^3$ configuration.
Surface States

The dangling bonds on the surface will take different electron configurations and generate surface states. The energy location of dangling bonds are directly related to the bulk band structure of the semiconductor. In the tight-binding formulism, the conduction bands and valence bands are formed as bonding and anti-bonding combination of the atomic $sp^3$ hybrids. Thus, these surface states are generally located in the middle of the energy bandgap. The Fermi level pinning positions of some III-V compounds are shown here. Since these experiments have to be done in vacuum, reliable data only available on (110) surface.
Surface States Modeled by Charge Neutrality Level (CNL)

- When forming hetero-interface, the energy band alignment is dictated by the pinning of interface states.
- The relative position of the surface states is defined, semi-empirically, by a reference level called charge neutrality level (CNL).
- The CNL is a weighted average of the density of states. It is repelled by large DOS in the valence and the conduction band. Therefore it is located inside the forbidden gap.

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The CNL value was determined by averaging values derived from various theoretical models. Calculated $E_{\text{CNL}}$ above $E_V$ of a number of common semiconductors are listed in the Table.

As expected, the Schottky barrier height on p-type material ($\phi_{\text{bv}}$) is very close to $E_{\text{CNL}}$.

These values are in good agreement with experimental data of surface states.

If the Fermi level is above the CNL ($E_{\text{CNL}}$), the surface states are of acceptor-like and negatively charged if the stats are occupied.

If the Fermi level is below $E_{\text{CNL}}$, the surface states are of donor-like and positively charged if the stats are occupied.

The surface states density ($D_{ss}$) distribution from valence band maximum to conduction band minimum (CBM) is parabolic in a logarithm scale.

A strong electron inversion occurs when the Fermi level reaches CBM.

<table>
<thead>
<tr>
<th>(eV)</th>
<th>$E_g$</th>
<th>$E_{\text{CNL}}$</th>
<th>$\phi_{\text{bv}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Ge</td>
<td>0.67</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>AlP</td>
<td>2.56</td>
<td>1.3</td>
<td>1.27</td>
</tr>
<tr>
<td>GaP</td>
<td>2.25</td>
<td>0.8</td>
<td>0.80</td>
</tr>
<tr>
<td>InP</td>
<td>1.34</td>
<td>0.6</td>
<td>0.86</td>
</tr>
<tr>
<td>AlAs</td>
<td>2.16</td>
<td>0.92</td>
<td>1.0</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.45</td>
<td>0.55</td>
<td>0.56</td>
</tr>
<tr>
<td>InAs</td>
<td>0.36</td>
<td>0.5</td>
<td>0.58</td>
</tr>
<tr>
<td>AlSb</td>
<td>1.7</td>
<td>0.4</td>
<td>0.47</td>
</tr>
<tr>
<td>GaSb</td>
<td>0.75</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>InSb</td>
<td>0.17</td>
<td>0.15</td>
<td>0.04</td>
</tr>
<tr>
<td>AlN</td>
<td>6.2</td>
<td></td>
<td>2.8</td>
</tr>
<tr>
<td>GaN</td>
<td>3.2</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>InN</td>
<td>0.76</td>
<td>1.87</td>
<td></td>
</tr>
</tbody>
</table>
Surface pinning in GaAs is very serious since the CBM and CNL difference is too large.

InGaAs has a much smaller CBM–CNL difference such that the unpinning of surface states is relatively easy to achieve.

Magnitude of \((E_C - E_{CNL})\) relates to \(D_{it}\).
III-V Compound Semiconductors: Lattice Constant
4.6.1. Lattice Constant – Vegard’s Law:
The lattice constant of multi-element alloys follow the so called “Vegard’s law”, where the lattice constant varies linearly with the composition.

- **Binary compounds:**
  For binary semiconductors, all physical parameters are fixed, i.e., zero degree of freedom.

- **Ternary alloys:**
  For ternary and quaternary alloys, there are added degree of freedom in tuning the band gap energy or (ternary) and (quaternary) the lattice constant. A ternary alloy $A_xB_{1-x}C$ formed by mixing two binaries, $AC$ and $BC$, where $A$ and $B$ are group-III elements and $C$ is a group-V element, can be seen as mixing $x$ fraction of $AC$ with $(1-x)$ fraction of $BC$.

  $$(AC)_x(BC)_{1-x}=A_xB_{1-x}C$$

  The lattice constant is expressed as

  $$a_o(x) = xa_{AC} + (1-x)a_{BC} = a_{BC} + (a_{AC} - a_{BC})x$$

  where $a_{AC}$ and $a_{BC}$ are lattice constants of $AC$ and $BC$, respectively. For a selected composition ($x$), the lattice constant and bandgap energy are fixed. It has one-degree of freedom in adjusting the physical parameters.
Bandgap Versus Lattice Constant
Quaternary Materials

- **Quaternary alloys:**
  Three ternary alloys or four binary alloys can form a quaternary alloy. It has two-degree of freedom. For a fixed lattice constant, a range of band gap energy ($E_g$) and chemical composition $(x, y)$ can be selected. There are three types of quaternary alloys according to their chemical constituents.

  - **III-III’-III”-V** type:
    It can be seen as the alloy of $(A^{III}D^{V})_x(B^{III}D^{V})_y(C^{III}D^{V})_{1-x-y}$, which gives an $A_xB_yC_{1-x-y}D$ quaternary such as $Al_xGa_yIn_{1-x-y}As$ and $Al_xGa_yIn_{1-x-y}P$.
    \[
    a_o(x,y) = xa_{AD} + ya_{BD} + (1-x-y)a_{CD}
    \]

  - **III-V-V’-V”** type:
    This alloy can be seen as the combination of $(A^{III}B^{V})_x(A^{III}C^{V})_y(A^{III}D^{V})_{1-x-y}$ which form an alloy of $AB_xC_yD_{1-x-y}$.
    \[
    a_o(x,y) = xa_{AB} + ya_{AC} + (1-x-y)a_{AD}
    \]
    This type of alloy is hard to prepare due to the presence of three high vapor pressure group-V elements.

  - **III-III’-V’-V”** type:
    This alloy is formed by mixing four binaries. For example, $Ga_xIn_{1-x}As_yP_{1-y}$ can be seen as a mixture of GaAs, InAs, GaP, and InP. In such a quaternary of $A^{III}B^{III}_xC^{V}_yD^{V}_{1-x-y}$, the lattice constant is expressed as
    \[
    a_o(x,y) = a_{AC}xy + a_{BC}(1-x)y + a_{AD}x(1-y) + a_{BD}(1-x)(1-y)
    \]
The lattice constant of the quaternary $Ga_xIn_{1-x}As_yP_{1-y}$ is expressed as

$$a_0(x,y) = 5.8687 - 0.4175x + 0.1896y + 0.0124xy$$

The projection of each lattice constant value in the base is a straight line. The shaded region shows the composition with a lattice constant of InP. The red contour shows compositions lattice match to GaAs.
Miscibility Gaps

• Miscibility gap concept:
  When mixing multiple elements into alloy, it has been assumed that the
distribution of the constituent elements follows the virtual-crystal model
and is uniform. However, studies using extended x-ray absorption fine-
structure (EXAFS) technique confirmed that the virtual-crystal assumption
of uniform mixing alloys is incorrect. The bond length of each binary
compound is almost a constant
independent of the ternary or quaternary alloys formed.

For certain ternary or quaternary
alloys, if the constituent binaries have
very different lattice constants, a
homogeneous alloy will not form over
a certain composition. For example,
when mixing GaAs (a_o=5.653Å) and
GaSb (a_o=6.10Å) to form GaAs_xSb_{1-x}
alloy, the ternary alloy of x≈50%
cannot be formed under equilibrium
growth condition.
Instead, it will form non-uniform material with two different compositions. The region where non-uniform alloys form is called the “miscibility gap”. The following figure shows the calculated spinodal critical (maximum) temperature contour for phase separation to occur at a specific alloy composition. For example, at growth temperatures below 50K, $GaAs_xSb_{1-x}$ shows a miscibility gap for $x > 22\%$. However, under normal growth condition, where $T_g >> 50K$, miscibility gap will not form in this material.
III-V Compound Semiconductors: Bandgap
Band Gap Energy

- **Bowling parameter:**
  As illustrated above, the crystal structures of ternary or quaternary alloys are not completely homogeneous but have certain degrees of randomness. This leads to a random fluctuation in the periodic lattice potential. Further, the bond length variation across the alloy induces local strains. This further disturbs the periodic lattice potential. As a result, the band gap energy versus composition relation does not follow the linear Vegard’s law and has a non-linear form of

\[ E_g = a + bx + cx^2 \]

where \( c \) is the **bowing parameter** - a non-linear term. So far, there is no valid model to determine the value of the bowing parameter for each ternary alloy. It has to be determined through experiments. (See \( E_g-x \) Table in class notes).

- **Direct-indirect crossover:**
  When mixing direct and indirect band gap binary compounds to form ternary alloy, the minimal band gap energy will have a portion of the composition shown direct (or indirect) property. This is due to the rate of energy band change as a function of composition for \( \Gamma, L \), and \( X \) valleys are different for the two binaries.
At a particular composition, the direct band gap energy equals to the indirect band gap value. This is the “crossover” composition. Further change the composition will drive the alloy into indirect band gap structure.
Bandgap of Quaternary Alloys

- Quaternary alloys:
  From the known $E_g - x$ values of ternary alloys, the $E_g$-composition relations of related quaternary can be calculated. For III-III’-V-V’ alloys, the bandgap are calculated using parameters of ternary alloys. (*J. Electron. Mater.* V.3, p.635, 1974)

\[
E_g(A_xB_{1-x}C_yD_{1-y}) = xE_{ACD} + (1-x)E_{BCD} - \Delta
\]

\[
\Delta = x(1-x)[(1-y)c_{ABD} + yc_{ABC}] + y(1-y)[xc_{ACD} + (1-x)c_{BCD}]
\]

where $c_{ABD}$, $c_{ABC}$, $c_{ACD}$ and $c_{BCD}$ are ternary bowing parameters.

The parameter of the same quaternary alloy $A_xB_{1-x}C_yD_{1-y}$ can also be obtained from the respective values of the four binaries $AC$, $AD$, $BC$, and $BD$ such that (*J. Electron. Mater.* V.7, p.6, 1978)

\[
E_g = xyE_{AC} + x(1-y)E_{AD} + (1-x)yE_{BC} + (1-x)(1-y)E_{BD}
\]

For III-III’-III”-V and III-V-V’-V” alloys, there is no available model for the band gap versus composition relation.

In general, the $E_g$-composition relation has to be determined experimentally coupled with a more complete expression such as

\[
E_g = a + bx + cy + dxy + ex^2 + fy^2 + gx^2y + hxy^2 + kx^2y^2
\]
Bandgap Surfaces

The 3D composition-band gap energy relation of the quaternary alloy $Ga_xIn_{1-x}As_yP_{1-y}$ is shown on the right. On each vertical side wall is the $E_g$-$x$ relation of a ternary alloy. The $E_g$-$x$ relations of four ternaries form the boundary of the quaternary energy surface.

Usually, we present the constant energy contours in a 2D plot as seen in next page. Each constant energy line is a projection of the constant energy intersection of the curved energy surface onto the base of the chart.

\[
E_g(Ga_xIn_{1-x}As_yP_{1-y}) = 1.35 + 0.668x - 1.068y - 0.069xy + 0.758x^2 + 0.078y^2 - 0.322x^2y + 0.03xy^2
\]
Bandgap Contour Plots for GaInAsP

- $E_g$ versus composition plot of $Ga_xIn_{1-x}As_yP_{1-y}$:
Bandgap Plots for III-III’-III”-V Materials

- $E_g$ versus composition plot of a III-III’-III”-V quaternary:
  This quaternary alloy can be seen as a mixture of three binaries with a
  common group-V anion. So the 3-D composition-band gap energy
  relation has a triangular cross-section.
  The 2-D plot of this quaternary
  is constructed following the
  same procedures as the
  III-III’-V-V’ alloy. The chemical
  composition $x$, $y$, and $z$ of
  $A_xB_yC_{1-x-y}D$ are determined
directly from the fraction of
each binary contained.
$E_g$ versus composition plot of $Al_xGa_yIn_{1-x-y}As$:
This quaternary is a mixture of $AlAs$, $GaAs$, and $InAs$ binaries.
### Bandgap Energy of Alloys

\[ \epsilon_g(\Gamma) = \Gamma_{6C} - \Gamma_{3V}, \quad \epsilon_g(X) = X_{6C} - \Gamma_{3V}, \quad \epsilon_g(L) = L_{6C} - \Gamma_{3V} \]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>( \epsilon_g(X) )</th>
<th>( \epsilon_g(\Gamma) )</th>
<th>( \epsilon_g(L) )</th>
<th>( x_c(\Gamma - X) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al(<em>2)Ga(</em>{1-x})P</td>
<td>( 2.28 + 0.16x )</td>
<td>( 1.420 + 1.087x + 0.438x^2 )</td>
<td>( 1.705 + 0.695x )</td>
<td>( x_c(\Gamma - L) = 0.47 )</td>
</tr>
<tr>
<td>Al(<em>2)Ga(</em>{1-x})As</td>
<td>( 1.905 + 0.10x + 0.16x^2 )</td>
<td>( 0.726 + 1.129x + 0.368x^2 )</td>
<td>( 1.020 + 0.492x + 0.077x^2 )</td>
<td>( x_c(\Gamma - L) = 0.43 )</td>
</tr>
<tr>
<td>Al(<em>2)Ga(</em>{1-x})Sb</td>
<td>( 0.799 + 0.746x + 0.334x^2 )</td>
<td>( 1.34 + 2.23x )</td>
<td>( 2.24 + 0.18x )</td>
<td>( x_c(\Gamma - L) = 0.44 )</td>
</tr>
<tr>
<td>Al(<em>2)In(</em>{1-x})P</td>
<td>( 0.37 + 1.91x + 0.74x^2 )</td>
<td>( 1.34 + 2.23x )</td>
<td>( 2.24 + 0.18x )</td>
<td>( x_c(\Gamma - L) = 0.68 )</td>
</tr>
<tr>
<td>Al(<em>2)In(</em>{1-x})As</td>
<td>( 1.8 + 0.4x )</td>
<td>( 0.37 + 1.91x + 0.74x^2 )</td>
<td>( 1.34 + 2.23x )</td>
<td>( x_c(\Gamma - L) = 0.44 )</td>
</tr>
<tr>
<td>Al(<em>2)In(</em>{1-x})Sb</td>
<td>( 0.172 + 1.621x + 0.43x^2 )</td>
<td>( 0.37 + 1.91x + 0.74x^2 )</td>
<td>( 1.34 + 2.23x )</td>
<td>( x_c(\Gamma - L) = 0.65 )</td>
</tr>
<tr>
<td>Al(<em>2)Ga(</em>{1-x})N</td>
<td>( 3.39 + 1.81x + bx^2 ) ((b = 1.0 \pm 0.3))</td>
<td>( 2.07 + 0.33x + 1.00x^2 )</td>
<td>( 1.351 + 0.643x + 0.786x^2 )</td>
<td>( x_c(\Gamma - L) = 0.73 )</td>
</tr>
<tr>
<td>Ga(<em>2)In(</em>{1-x})N</td>
<td>( 2.07 + 0.33x + 1.00x^2 )</td>
<td>( 3.39 + 1.81x + bx^2 ) ((b = 1.0 \pm 0.3))</td>
<td>( 2.07 + 0.33x + 1.00x^2 )</td>
<td>( x_c(\Gamma - L) = 0.65 )</td>
</tr>
<tr>
<td>Ga(<em>2)In(</em>{1-x})P</td>
<td>( 1.351 + 0.643x + 0.786x^2 )</td>
<td>( 2.07 + 0.33x + 1.00x^2 )</td>
<td>( 3.39 + 1.81x + bx^2 ) ((b = 1.0 \pm 0.3))</td>
<td>( x_c(\Gamma - L) = 0.73 )</td>
</tr>
<tr>
<td>Ga(<em>2)In(</em>{1-x})As</td>
<td>( 2.24 + 0.02x )</td>
<td>( 1.351 + 0.643x + 0.786x^2 )</td>
<td>( 2.07 + 0.33x + 1.00x^2 )</td>
<td>( x_c(\Gamma - L) = 0.65 )</td>
</tr>
<tr>
<td>Ga(<em>2)In(</em>{1-x})Sb</td>
<td>( 0.324 + 0.7x + 0.4x^2 )</td>
<td>( 2.24 + 0.02x )</td>
<td>( 1.351 + 0.643x + 0.786x^2 )</td>
<td>( x_c(\Gamma - L) = 0.65 )</td>
</tr>
<tr>
<td>Ga(<em>2)As(</em>{1-x})P</td>
<td>( 0.172 + 0.139x + 0.415x^2 )</td>
<td>( 0.324 + 0.7x + 0.4x^2 )</td>
<td>( 2.24 + 0.02x )</td>
<td>( x_c(\Gamma - L) = 0.65 )</td>
</tr>
<tr>
<td>Ga(<em>2)As(</em>{1-x})x(_{1-x})</td>
<td>( 1.424 + 1.150x + 0.176x^4 )</td>
<td>( 0.172 + 0.139x + 0.415x^2 )</td>
<td>( 0.324 + 0.7x + 0.4x^2 )</td>
<td>( x_c(\Gamma - L) = 0.65 )</td>
</tr>
</tbody>
</table>

A recent complete review on bandgap energy of III-V alloys can be found in *J. Appl. Phys.* Vol. 89, pp.5816 (2001) by Vurgaftman, Meyer and Ram-Mohan.
Bandgap Energy of Alloys (2)

\[ \epsilon_G(\Gamma) = \Delta_{6C} - \Delta_{8V}, \quad \epsilon_G(X) = \Delta_{6C} - \Delta_{8V}, \quad \epsilon_G(L) = L_{6C} - \Delta_{8V} \]

<table>
<thead>
<tr>
<th>Compound</th>
<th>( \epsilon_G(\Gamma) )</th>
<th>( \epsilon_G(X) )</th>
<th>( \epsilon_G(L) )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs(_{1-x})Sb(_x)</td>
<td>( 1.43 - 1.9x + 1.2x^2 )</td>
<td></td>
<td></td>
<td>(119)</td>
</tr>
<tr>
<td>InAs(_{1-x})P(_x)</td>
<td>( 0.356 + 0.675x + 0.32x^2 )</td>
<td></td>
<td></td>
<td>(120)</td>
</tr>
<tr>
<td>InAs(_{1-x})Sbx</td>
<td>( 0.18 - 0.41x + 0.58x^2 )</td>
<td></td>
<td></td>
<td>(121)</td>
</tr>
<tr>
<td>Ga(<em>x)In(</em>{1-x})As(<em>y)P(</em>{1-y})</td>
<td>\begin{align*} \epsilon_G(\Gamma) &amp;= 1.35 + 0.668x - 1.068y + 0.758x^2 + 0.078y^2 + 0.069xy - 0.322x^2y + 0.03xy^2 \ \epsilon_G(X) &amp;= 1.35 - 0.775y + 0.149y^4 (x \approx 0.47y : \text{match to InP}) \end{align*}</td>
<td></td>
<td></td>
<td>(122)</td>
</tr>
<tr>
<td>Al(_x)Ga(<em>y)In(</em>{1-x-y})P</td>
<td>( 1.9 + 0.6z (x + y = 0.51, x = 0.51z : \text{match to GaAs}) )</td>
<td></td>
<td>( z_G(\Gamma-X) = 0.66 )</td>
<td>(59)</td>
</tr>
<tr>
<td>Al(_x)Ga(<em>y)In(</em>{1-x-y})As</td>
<td>\begin{align*} \epsilon_G(\Gamma) &amp;= 0.36 + 2.093x + 0.629y + 0.577x^2 + 0.436y^2 + 1.013xy - 2.0xy(1-x-y) \ \epsilon_G(X) &amp;= 0.764 + 0.495z + 0.203z^2 \ &amp;\quad (0.98x + y = 0.47, x = 0.48z : \text{match to InP}) \end{align*}</td>
<td></td>
<td></td>
<td>(123)</td>
</tr>
<tr>
<td>Al(_x)Ga(<em>y)In(</em>{1-x-y})Sb</td>
<td>\begin{align*} \epsilon_G(\Gamma) &amp;= 0.095 + 1.76x + 0.28y + 0.345(x^2 + y^2) + 0.085x^2 + xy(23 - 28y) + 0.345(z = 1 - x - y) \ \epsilon_G(X) &amp;= 1.0675 + 0.30x - 0.31y + 0.2625(x^2 + y^2 + x^2) + xy(20x - 5.9) \end{align*}</td>
<td></td>
<td></td>
<td>(124)</td>
</tr>
<tr>
<td>II—VI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZnS(_{1-x})Se(_x)</td>
<td>( 2.791 + 0.592x + 0.41x^2 (77K) )</td>
<td></td>
<td></td>
<td>(126)</td>
</tr>
<tr>
<td>Cd(_{1-x})Zn(_x)Te</td>
<td>( 1.510 + 0.606x + 0.139x^2 )</td>
<td></td>
<td></td>
<td>(127)</td>
</tr>
<tr>
<td>Si(<em>x)Ge(</em>{1-x})</td>
<td>\begin{align*} \epsilon_G(\Gamma) &amp;= 0.894 + 0.042x + 0.169x^2 (0K, \ldots) \ \epsilon_G(X) &amp;= 0.894 + 0.042x + 0.169x^2 (0K, \ldots) \end{align*}</td>
<td></td>
<td></td>
<td>(128)</td>
</tr>
</tbody>
</table>
### Effective Mass and Dielectric Constant

<table>
<thead>
<tr>
<th></th>
<th>( m_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Al(<em>x)Ga(</em>{1-x})As</strong></td>
<td>( m^*_{e}(\Gamma) = 0.067 + 0.083x )</td>
</tr>
<tr>
<td></td>
<td>( m^*_{e}(X) = 0.85 - 0.14x )</td>
</tr>
<tr>
<td></td>
<td>( m^*_{e}(L) = 0.56 + 0.1x )</td>
</tr>
<tr>
<td></td>
<td>( m^*_{hh} = 0.62 + 0.14x )</td>
</tr>
<tr>
<td></td>
<td>( m^*_{lh} = 0.087 + 0.063x )</td>
</tr>
<tr>
<td></td>
<td>( m^*_{soh} = 0.15 + 0.09x )</td>
</tr>
<tr>
<td><strong>GaAs(_{1-x})Sb(_x)</strong></td>
<td>( m^*_{e} = 0.0634 - 0.0483x + 0.0252x^2 )</td>
</tr>
<tr>
<td><strong>Ga(<em>x)In(</em>{1-x})As(<em>y)P(</em>{1-y})</strong></td>
<td>( m^*_{e} = 0.08 - 0.116x + 0.026y - 0.059xy )</td>
</tr>
<tr>
<td></td>
<td>( + (0.064 - 0.02x)y^2 + (0.06 + 0.032y)x^2 )</td>
</tr>
<tr>
<td></td>
<td>( m^*_{e} = 0.077 - 0.050y + 0.014y^2 )</td>
</tr>
<tr>
<td></td>
<td>( (x \approx 0.47y : \text{match to InP}) )</td>
</tr>
<tr>
<td><strong>Al(_x)Ga(<em>y)In(</em>{1-x-y})As</strong></td>
<td>( m^*_{e} = 0.0427 + 0.0328z )</td>
</tr>
<tr>
<td></td>
<td>( (0.98x + y = 0.47, x = 0.48z : \text{match to InP}) )</td>
</tr>
</tbody>
</table>

|                | \( \varepsilon_0 = 13.18 - 3.12x \) |
|                | \( \varepsilon_\infty = 10.89 - 2.78x \) |
| **Al\(_x\)Ga\(_{1-x}\)As** | \( \varepsilon_0 = 12.40 + 1.5y \) |
|                | \( \varepsilon_\infty = 9.55 + 2.2y \) |
|                | \( (x \approx 0.47y : \text{match to InP}) \) |
III-N Materials
III-N Compounds

4.7.1. III-Nitride Compounds


All III-N’s can form either wurtzite or zinc-blende structure depending on growth conditions and substrate structure with the wurtzite as the favored structure.
Bandgap Energy of III-N Alloys

The bandgap energy as a function of temperature follows the following form.

\[ E_g(T) = E_g(T=0) - \frac{\alpha T^2}{T + \beta} \]

The data listed in the following tables are the lattice constant and energy gap values of GaN, AlN, and InN with wurtzite and zinc-blende crystal structures.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>GaN</th>
<th>AlN</th>
<th>InN</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_{lc} ) (Å) at ( T=300 ) K</td>
<td>3.189</td>
<td>3.112</td>
<td>3.545</td>
</tr>
<tr>
<td>( c_{lc} ) (Å) at ( T=300 ) K</td>
<td>5.185</td>
<td>4.982</td>
<td>5.703</td>
</tr>
<tr>
<td>( E_g ) (eV)</td>
<td>3.510</td>
<td>6.25</td>
<td>0.78</td>
</tr>
<tr>
<td>( \alpha ) (meV/K)</td>
<td>0.909</td>
<td>1.799</td>
<td>0.245</td>
</tr>
<tr>
<td>( \beta ) (K)</td>
<td>830</td>
<td>1462</td>
<td>624</td>
</tr>
</tbody>
</table>

Dopant:

n-type: Si, Ge
p-type: Mg with annealing
Bandgap Energy Variation: III-N Ternaries

The bandgap energy variation between two III-N binary compounds follows the equation below with a bowing parameter $C$.

$$E_g(A_{1-x}B_x) = (1-x)E_g(A) + xE_g(B) - x(1-x)C,$$

The bowing parameters for GaInN, AlGaN, and AlInN are listed below. The parameter $P_{sp}$ is the bowing parameter of spontaneous polarization. Since the III-N alloys have been under intensive studies over the past short ten years, one should check the listed data with new experimental results for accuracy.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>GaInN (eV)</th>
<th>AlGaN (eV)</th>
<th>AlInN (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g^T$</td>
<td>1.4</td>
<td>0.7</td>
<td>2.5</td>
</tr>
<tr>
<td>$E_g^X$</td>
<td>0.69</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>$E_g^L$</td>
<td>1.84</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>$P_{sp}$</td>
<td>-0.037</td>
<td>-0.021</td>
<td>-0.070</td>
</tr>
</tbody>
</table>
Dilute Nitrides: III-V-N Compounds
When mixing III-V compounds with a small fraction (usually \( \leq 2-3\% \)) of nitrogen such as \( \text{GaAs}_x\text{N}_{1-x} \) and \( \text{GaP}_x\text{N}_{1-x} \), a very large bowing parameter exists. This unusual behavior is probably due to the extremely large bond length difference between N and other group-V elements and/or the unique isoelectronic property of N in III-V alloys. Since N atoms have the same valence as the host group-V atoms, the localized potential field/energy state can interact with the conduction band and form new band structure. The band gap of the alloy has value smaller than either constituent binaries. The drastically reduced band gap energy offers new application opportunities. For example, long wavelength (\( \geq 1.3\mu\text{m} \)) light emission materials of dilute nitrides \( (\text{As}_x\text{N}_{1-x}) \) can be grown lattice matched to high quality GaAs substrates.
GaInNAs:GaAs for Telecom Lasers

Desired fiber wavelengths:
- Dispersion zero
- Attenuation minimum

Devices Grown on GaAs
- Cheap substrates
- Superior thermal properties (large $\Delta E_C$, $T_0=250K$)
- GaAs/AlAs DBRs
GaP$_{1-x}$N$_x$ and GaAs$_{1-x}$N$_x$ Dilute Nitrides

- $GaP_{1-x}N_x$ was first demonstrated at UIUC in 1991.
- $GaAs_{1-x}N_x$ was later developed by Kondow of Hitachi in 1994.

Band Anticrossing Model

The large bandgap energy reduction in dilute nitrides is explained with a band anti-crossing (BAC) model proposed by Shan in 1999 (Phys. Rev. Lett, vol.82, p.1221). The interaction between the conduction band and the nitrogen states splits the conduction band into two subbands and reduces the fundamental band gap.

\[ E_\pm(k) = \frac{1}{2} \left\{ [E_C^C(k) + E_N^N] \pm \sqrt{[E_C^C(k) - E_N^N]^2 + 4V^2x} \right\} \]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( E_N ) w. r. t. VBM (eV)</th>
<th>( V ) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAsN</td>
<td>1.65</td>
<td>2.7</td>
</tr>
<tr>
<td>InAsN</td>
<td>1.44</td>
<td>2.0</td>
</tr>
<tr>
<td>Ga(_{1-x})In(_x)AsN</td>
<td>1.65(1-x) + 1.44x - 0.38x(1-x)</td>
<td>2.7(1-x) + 2.0x - 3.5x(1-x)</td>
</tr>
<tr>
<td>GaPN</td>
<td>2.18</td>
<td>3.05</td>
</tr>
<tr>
<td>InPN</td>
<td>1.79</td>
<td>3.0</td>
</tr>
<tr>
<td>Ga(_{1-x})In(_x)PN</td>
<td>2.18(1-x) + 1.79x</td>
<td>3.05(1-x) + 3.0x - 3.3x(1-x)</td>
</tr>
<tr>
<td>InSbN</td>
<td>0.65</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Agenda for Next Class

• Group IV Materials
Thank You!
Final Exam

<table>
<thead>
<tr>
<th>Course</th>
<th>Section</th>
<th>CRN</th>
<th>Date</th>
<th>Day</th>
<th>Start Time</th>
<th>End Time</th>
<th>Room</th>
<th>Exam Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECE 488</td>
<td>C</td>
<td>66375</td>
<td>12/12/2016</td>
<td>M</td>
<td>7:00 PM</td>
<td>10:00 PM</td>
<td>3017 Electrical &amp; Computer Eng Bldg</td>
<td>Extra Space</td>
</tr>
</tbody>
</table>
# Periodic Table of the Elements

<table>
<thead>
<tr>
<th>Period</th>
<th>Group</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA</td>
<td>I</td>
<td>H, He</td>
</tr>
<tr>
<td>IIA</td>
<td>II</td>
<td>Li, Be, Mg, Ca, Sr, Ba, Ra</td>
</tr>
<tr>
<td>IIA</td>
<td>IIIB</td>
<td>Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu</td>
</tr>
<tr>
<td>IIA</td>
<td>IIIC</td>
<td>Zn, Cd, Hg</td>
</tr>
<tr>
<td>IIA</td>
<td>IV</td>
<td>Ag, Au</td>
</tr>
<tr>
<td>IIA</td>
<td>V</td>
<td>Tl, Pb, Bi</td>
</tr>
<tr>
<td>IIA</td>
<td>VI</td>
<td>Hg, Tl, Pb, Bi</td>
</tr>
<tr>
<td>IIA</td>
<td>VII</td>
<td>Rn, Fr, Ra</td>
</tr>
<tr>
<td>IIA</td>
<td>VII</td>
<td>Ra</td>
</tr>
</tbody>
</table>

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

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
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, 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>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**
## Tentative Schedule [3]

<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>
</tr>
<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>
</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: