ECE 488: Compound Semiconductors

M,W,F 11:00 – 11:50, 3013 ECEB
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Office Hours: Tuesday 13:00 – 14:00
Lecture 32: November 7th, 2016
Assignments

• Reading from “Compound Semiconductors and Devices – An Introduction”
  – Mon 10/31: §’s 8.1, 8.1.1, 8.1.2, 8.1.3, 8.1.4, 8.1.5
  – Wed 11/2: §’s 8.2, 8.2.1, 8.2.2, 8.2.3, 8.2.4
  – Fri 11/4: §’s 8.3, 8.3.1, 8.3.2, 8.3.3
  – Mon 11/7: §’s 8.4, 8.4.1, 8.4.2, 8.4.3, 8.5
  – Fri 11/11: §’s 9.3, 9.3.1, 9.3.2

• Homework: Posted Friday 11-3, Due 11-11

• Quiz: Tentative Date is Wednesday Nov. 16th
Today’s Agenda

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

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Electrical Properties of Heterostructures

Continued
7.2.1. Potential distribution profile:

Under an applied bias, $V_a$ ($V_f$ or $-V_r$), the potential profile and depletion width are modified. The distribution of the applied bias in $p$ and $N$-side are $V_1$ and $V_2$, respectively. Thus, $V_a = V_1 + V_2$, and $V_p$ and $V_N$ are changed to $(V_p - V_1)$ and $(V_N - V_2)$, respectively. Thus, the new potential drops at the heterojunction ($x=0$) are

$$V_p(0) = V_p - V_1 = \frac{qN_a}{2\varepsilon_p} (x_p)^2$$

$$V_N(0) = V_N - V_2 = \frac{qN_D}{2\varepsilon_N} (x_N)^2$$

where $x_p$ and $x_N$ are the modified depletion widths under $(V_o - V_a)$. Otherwise, they have the same form as for the unbiased junction.
Potential Distribution

\[ x_N = \left[ \frac{2(V_o - V_a)\varepsilon_N\varepsilon_p}{qN_D} \left( \frac{N_a}{\varepsilon_p N_a + \varepsilon_N N_D} \right) \right]^{1/2}; \quad x_p = \left[ \frac{2(V_o - V_a)\varepsilon_N\varepsilon_p}{qN_a} \left( \frac{N_D}{\varepsilon_p N_a + \varepsilon_N N_D} \right) \right]^{1/2} \]

Take the ratio of \( V_p(0) \) and \( V_N(0) \) and apply the charge neutrality condition.

\[ \frac{V_N(0)}{V_p(0)} = \frac{V_N - V_2}{V_p - V_1} = \frac{\varepsilon_p N_D (x_N)^2}{\varepsilon_N N_a (x_p)^2} = \frac{\varepsilon_p N_a}{\varepsilon_N N_D} \]

Since \( V_o - V_a = (V_p - V_1) + (V_N - V_2) \)

\[ \therefore \quad \frac{V_o - V_a}{V_p - V_1} = 1 + \frac{V_N - V_2}{V_p - V_1} = 1 + \frac{\varepsilon_p N_a}{\varepsilon_N N_D} \]

\[ \Rightarrow \quad V_p - V_1 = \frac{V_o - V_a}{1 + \left( \frac{\varepsilon_p N_a}{\varepsilon_N N_D} \right)} \]

By the same method, we can also calculate \( V_2 \).

\[ \frac{V_o - V_a}{V_N - V_2} = 1 + \frac{V_p - V_1}{V_N - V_2} = 1 + \frac{\varepsilon_N N_D}{\varepsilon_p N_a} \]

\[ \Rightarrow \quad V_N - V_2 = \frac{V_o - V_a}{1 + \left( \frac{\varepsilon_N N_D}{\varepsilon_p N_a} \right)} \]
Carrier Injection: pN Heterojunction

Basic assumptions are similar to homojunction diodes:

- Non-degenerate materials (Boltzmann approximation applies)
- Low-level injection condition (minority density $< \Delta E_{HP} <$ majority density)
- Abrupt depletion region ($F=0$ outside the depletion region)
- Ideal junction (no generation/recombination currents in depletion region)
Minority Carrier Concentration

The procedures of deriving the current-voltage relationship in a $p-N$ heterojunction is similar to that of homojunctions.

1. The minority carrier concentration at the edge of the depletion region is derived first.

2. The minority carrier diffusion current will then be derived.

The majority carrier concentration is a constant in the bulk and at the edge of the depletion region:

$$n_{No} = N_{cN} \exp\left(\frac{E_{FN} - E_{cN}}{kT}\right) \quad \text{and} \quad p_{po} = N_{vp} \exp\left(\frac{E_{vp} - E_{FP}}{kT}\right)$$

The corresponding minority carrier concentrations are

$$p_{No} = \left(\frac{n_{iN}}{n_{No}}\right)^2 \quad \text{and} \quad n_{po} = \left(\frac{n_{ip}}{p_{po}}\right)^2$$

The majority carrier concentration can also expressed in terms of the intrinsic energy level, $E_i$ and the intrinsic carrier concentration, $n_i$.

$$n_{No} = n_{iN} \exp\left(\frac{E_{FN} - E_{iN}}{kT}\right) \quad \text{and} \quad p_{po} = n_{ip} \exp\left(\frac{E_{ip} - E_{FP}}{kT}\right)$$

Under low-level injection condition, the change in majority carrier concentration in the bulk is negligible and the majority carrier concentration maintains a constant in the bulk up to the edge of the depletion region.
Minority Carrier Concentration (2)

\[ n_N = n_{No} \approx N_D \quad \text{at} \quad x \geq x_N \]
\[ p_p = p_{po} \approx N_a \quad \text{at} \quad x \leq -x_p \]

Since there is no generation/recombination in the depletion region, the quasi-Fermi level, \( q\phi(x) \), maintains the same height as the bulk Fermi level and extends into the depletion region.

\[ q\phi_N(x) = E_{FN} \quad \text{for} \quad x \geq -x_p \]
\[ q\phi_p(x) = E_{Fp} \quad \text{for} \quad x \leq x_N \]

In terms of quasi-Fermi level, the majority and minority carrier concentrations at the edge of depletion region at \( x = x_N \) are rewritten as

\[ n_N = n_{iN} \exp\left(\frac{q\phi_{No} - E_{iN}}{kT}\right) \quad \text{and} \quad p_N = n_{iN} \exp\left(\frac{E_{iN} - q\phi_{po}}{kT}\right) \]

where \( \phi_{No} \) and \( \phi_{po} \) are quasi-Fermi levels for electrons and holes just outside of the depletion region, respectively, on the \( N \)-side.

\[ n_N p_N = (n_{iN})^2 \exp\left(\frac{q\phi_{No} - E_{iN} + E_{iN} - q\phi_{po}}{kT}\right) = (n_{iN})^2 \exp\left(\frac{q\phi_{No} - q\phi_{po}}{kT}\right) \]

\[ n_N p_N = (n_{iN})^2 \exp\left(\frac{qV_a}{kT}\right) \neq (n_{iN})^2 \]

where \( qV_a = q\phi_{No} - q\phi_{po} = E_{FN} - E_{Fp} \).
Therefore, at the edges of the depletion region, the minority carrier concentrations are

\[ p_N = \frac{(n_i N)^2}{n_N} \exp\left(\frac{qV_a}{kT}\right) = p_{N0} \exp\left(\frac{qV_a}{kT}\right) \quad \text{at} \quad x = x_N \]

\[ n_p = n_{p0} \exp\left(\frac{qV_a}{kT}\right) \quad \text{at} \quad x = -x_p \]

The important outcome is that the minority carrier concentration increases exponentially with the applied bias \( V_a \). This is similar to a homojunction diode.

(b). **Injected current densities across the p-N heterojunction:**
Consider an one-dimensional case, the current flow, \( j \), is related to minority carrier density variation through the continuity equation.

\[
\begin{align*}
\frac{\partial n}{\partial t} &= + \frac{1}{q} \frac{\partial j_n}{\partial x} + g(x) - \frac{n - n_o}{\tau_n} \\
\frac{\partial p}{\partial t} &= - \frac{1}{q} \frac{\partial j_p}{\partial x} + g(x) - \frac{p - p_o}{\tau_p}
\end{align*}
\]

Where \( g(x) \) is the generation rate in the depletion region, \( n_o \) and \( p_o \) are the equilibrium minority carrier concentration, and \( \tau_n \) and \( \tau_p \) are carrier lifetime. Under steady state condition and without external excitation, \( \partial / \partial t = 0 \) and \( g(x) = 0 \).
The current densities contain both diffusion and drift terms and are given by

\[
\begin{align*}
  j_n &= q\mu_n n F + q D_n \frac{dn}{dx} \\
  j_p &= q\mu_p p F - q D_p \frac{dp}{dx}
\end{align*}
\]

In neutral regions, \( F = 0 \), where minority carriers are injected into, only the diffusion term is considered. Therefore, the continuity equations reduce to

\[
\begin{align*}
  D_n \frac{\partial^2 n}{\partial x^2} - \frac{n - n_o}{\tau_n} &= 0 \\
  D_p \frac{\partial^2 p}{\partial x^2} - \frac{p - p_o}{\tau_p} &= 0
\end{align*}
\]

The minority electron concentration in the \( p \)-type neutral region, \( n_o = n_{po} \), can be solved as

\[
  n(x) = C_1 \exp\left( -\frac{x}{\sqrt{D_n \tau_n}} \right) + C_2 \exp\left( \frac{x}{\sqrt{D_n \tau_n}} \right) + n_{po}
\]

The constants \( C_1 \) and \( C_2 \) can be solved in the \( p \)-side by using boundary conditions of \( n(x=-\infty) = n_{po} \) and \( n(-x_p) = n_{po} \exp(qV_d/kT) \).

\[
\begin{align*}
  C_1 &= 0 \\
  C_2 &= n_{po} \exp\left( \frac{x_p}{\sqrt{D_n \tau_n}} \right) \left( \exp\left( \frac{qV_a}{kT} \right) - 1 \right)
\end{align*}
\]
Total Current Density

The injected minority electron distribution in the \( p \)-region becomes

\[
n(x) - n_{po} = n_{po} \exp\left(\frac{x_p + x}{L_n}\right) \exp\left(\frac{qV_d}{kT} - 1\right) \quad \text{and} \quad L_n \equiv \sqrt{D_n \tau_n}
\]

In the neutral region, \( F=0 \), only the diffusion current exists.

\[
J_n(-x_p) = q D_n \frac{dn}{dx} \bigg|_{-x_p} = q D_n \left( \frac{n_{po}}{L_n} \exp\left(\frac{qV_d}{kT} - 1\right) \right) \exp\left(\frac{x_p + x}{L_n}\right) \bigg|_{-x_p}
\]

Finally, the minority induced injection current densities at edges of the depletion region are obtained.

\[
\begin{align*}
J_n(-x_p) &= \frac{q D_n}{L_n} n_{po} \exp\left(\frac{qV_d}{kT} - 1\right) \\
J_p(x_N) &= \frac{q D_p}{L_p} p_{No} \exp\left(\frac{qV_d}{kT} - 1\right)
\end{align*}
\]

The total current density in a \( p-N \) junction is the sum of both electron and hole minority current densities at the edges of the depletion region.

\[
J = J_n(-x_p) + J_p(x_N) = \left( \frac{q D_n}{L_n} n_{po} + \frac{q D_p}{L_p} p_{No} \right) \exp\left(\frac{qV_d}{kT} - 1\right)
\]

\[
J = J_0 \exp\left(\frac{qV_d}{kT} - 1\right)
\]

This is the same current-voltage characteristic for a homojunction diode.
Electron-Hole Current Ratio

The similarity of the I-V characteristic between homo- and heterojunction diodes stops here. The influence of heterojunction on current injections is revealed from the ratio of electron and hole current components.

\[
\frac{j_n}{j_p} = \frac{D_n L_p}{D_p L_n} \frac{n_{po}}{p_{po}} \frac{D_n}{D_p} \frac{L_p}{L_n} \frac{\left(n_{ip}\right)^2}{\left(n_{iN}\right)^2} n_{No} p_{No} = N_{cN} N_{vN} \exp\left(-\frac{E_{gN}}{kT}\right)
\]

For

\[
\left(n_{iN}\right)^2 = n_{No} p_{No} = N_{cN} N_{vN} \exp\left(-\frac{E_{gN}}{kT}\right)
\]

\[
\left(n_{ip}\right)^2 = n_{po} p_{po} = N_{cp} N_{vp} \exp\left(-\frac{E_{gp}}{kT}\right)
\]

\[
\Rightarrow \frac{j_n}{j_p} = \frac{D_n L_p}{D_p L_n} \frac{n_{No}}{p_{po}} \frac{N_{cp} N_{vp}}{N_{cN} N_{vN}} \exp\left(-\frac{E_{gN} - E_{gp}}{kT}\right)
\]

The exponential term dominates the current density ratio.

For \(E_{gN} > E_{gp}\), \(j_N >> j_p\). Or, the current dominates by the large bandgap material.

In homojunction diodes, \(E_{gN} = E_{gp} = E_g\), \(N_{cN} = N_{cp} = N_c\), and \(N_{vN} = N_{vp} = N_v\).

\[
\frac{j_n}{j_p} = \frac{D_n L_p}{D_p L_n} \frac{n_{No}}{p_{po}} \frac{D_n L_p}{D_p L_n} \frac{N_d}{N_a} \approx \text{constant}
\]
Realistic Finite Wells
Infinite Quantum Well

In infinite deep QWs, we only consider waves inside the QW and neglect any wave penetrating into barriers. The potential function depends on z-direction only and has no electron barriers in x- and y-directions. The electron movement is restricted only in z-direction but moving freely in the other two directions. Thus, the solutions of the wave function $\psi(r)$ in x- and y-directions are plane waves, while $\psi(z)$ is a standing wave.

$$\psi(x, y, z) = \exp(ik_x x)\exp(ik_y y)\phi(z)$$

The Schrödinger equation becomes

$$\left[\frac{\hbar^2 k_x^2}{2m_w^*} + \frac{\hbar^2 k_y^2}{2m_w^*} - \frac{\hbar^2}{2m_w^*} \frac{d^2}{dz^2} + V(z)\right]\phi(z) = E\phi(z)$$

where $m_w^*$ is the effective mass of the quantum well material. Since the first two terms in the bracket on the LHS are constants, we can rearrange the equation such that all constants are on the RHS.

$$\left[-\frac{\hbar^2}{2m_w^*} \frac{d^2}{dz^2} + V(z)\right]\phi(z) = \left[E - \frac{\hbar^2 k_x^2}{2m_w^*} - \frac{\hbar^2 k_y^2}{2m_w^*}\right]\phi(z) = \varepsilon_n\phi(z)$$
The wave function and energy solutions inside the QW, $-L/2 \leq z \leq L/2$, are

$$\psi_n(x,y,z) = \exp(ik_xx)\exp(ik_yy)\sqrt{\frac{2}{L}} \sin\left(\frac{n\pi}{L}z\right)$$

$$E_n = \frac{\hbar^2}{2m_w^*} \left[ k_x^2 + k_y^2 + \left(\frac{n\pi}{L}\right)^2 \right]$$

$$\varepsilon_n = \frac{\hbar^2}{2m_w^*} \left(\frac{n\pi}{L}\right)^2 \quad n = 1, 2, 3, 4\ldots$$

The energy function is discrete in $z$-direction, but is parabolic in both $x$- and $y$-directions.

Note: Finite well shown.
Finite Square Well

\[ V = V_o \]

Now we have to consider the evanescent waves. In both barrier layers, the wave functions, \( \psi_\pm \), are decaying functions and have the form of

\[ \psi_\pm (|z| \geq L/2) = A \exp(\mp \alpha z); \quad \alpha = \sqrt{2m^*(V_o - E)/\hbar^2} \]

The penetration depth for a GaAs/AlGaAs QW can be calculated using a typical barrier height of \( V_o \approx 0.3eV \), and \( m^* = 0.067m_o \). For a small \( E_1 \approx 0 \) (ground state), the possible maximum value of \( \alpha \) is \( 7.26 \times 10^8 \text{ cm}^{-1} \). The amplitude of the wave function drops to \( 1/e \) at the smallest \( z = 1/\alpha = 1.38 \text{ nm} \) \( \sim 5 \)-monolayer (ML). Considering a typical QW with a thickness of \( \sim 20 \) to \( 30 \) MLs, we have to calculate exact solutions to solve \( \psi(z) \). Due to the different masses in the QW and barriers, some modifications to the finite well solution with constant effective mass are needed.
Finite Square Well (2)

- Inside the QW, \(-L/2 \leq z \leq L/2\):
  \[
  \frac{d^2 \psi_o}{dz^2} + \alpha^2 \psi_o = 0; \quad \alpha = \sqrt{2m_w^*E/\hbar^2}
  \]
  \[
  \Rightarrow \quad \psi_o = \begin{cases} 
  A \cos(\alpha z) & \text{even function} \\
  A \sin(\alpha z) & \text{odd function}
  \end{cases}
  \]

- Outside the QW (inside barriers), \(z \leq -L/2\) and \(z \geq L/2\):
  \[
  \frac{d^2 \psi_\pm}{dz^2} - \beta^2 \psi_\pm = 0; \quad \beta = \sqrt{2m_b^*(V_o - E)/\hbar^2}
  \]
  \[
  \Rightarrow \quad \psi_\pm = \begin{cases} 
  B \exp[-\beta(z - L/2)] & z > L/2 \\
  B \exp[+\beta(z + L/2)] & z < -L/2
  \end{cases}
  \]

To solve constants \(A\) and \(B\), the connection conditions across the barrier-well interfaces have to be modified due to mass change.

At \(z = -L/2\) and \(z = L/2\),

\[
\begin{align*}
\psi_o \bigg|_{z=\pm L/2} &= \psi_\pm \bigg|_{z=\pm L/2} \\
\frac{1}{m_w^*} \frac{d \psi_o}{dz} \bigg|_{z=\pm L/2} &= \frac{1}{m_b^*} \frac{d \psi_\pm}{dz} \bigg|_{z=\pm L/2}
\end{align*}
\]

\(m_w^*\) and \(m_b^*\) are effective masses in the QW and barrier layer, respectively.
Finite Square Well (3)

For the even wave function at \( z = L/2 \), the boundary conditions give

\[
\begin{align*}
A \cos \left( \frac{\alpha L}{2} \right) &= B \\
-\frac{\alpha A}{m_w^*} \sin \left( \frac{\alpha L}{2} \right) &= -\frac{\beta B}{m_b^*}
\end{align*}
\]

Eliminate \( A \) and \( B \), we have the following solution for the even function.

\[
\beta = \left( \frac{m_b^*}{m_w^*} \right) \alpha \tan \left( \frac{\alpha L}{2} \right)
\]

Similarly, we can solve the odd wave function as:

\[
\beta = -\left( \frac{m_b^*}{m_w^*} \right) \alpha \cot \left( \frac{\alpha L}{2} \right)
\]

These two equations have no analytical solutions and a graphic or numerical method has to be used. Focus on the even function again and multiply \((L/2)\) to the above equation.

\[
\frac{\beta L}{2} = \left( \frac{m_b^*}{m_w^*} \right) \alpha \left( \frac{L}{2} \right) \tan \left( \frac{\alpha L}{2} \right)
\]

or

\[
\left( \beta \sqrt{\frac{m_w^*}{m_b^*}} \right) \frac{L}{2} = \beta' \frac{L}{2} = \sqrt{\frac{m_b^*}{m_w^*}} \left( \frac{\alpha L}{2} \right) \tan \left( \frac{\alpha L}{2} \right)
\]
Finite Square Well (4)

\[
\frac{\beta' L}{2} = \sqrt{\frac{m_b^*}{m_w^*} \left( \frac{\alpha L}{2} \right) \tan \left( \frac{\alpha L}{2} \right)} \quad \text{and} \quad \beta' = \beta \sqrt{\frac{m_w^*}{m_b^*}}
\]

This equation is similar to that for an ideal QW \((\eta = \xi \tan \xi)\). Also,

\[
\alpha^2 + \beta'^2 = \frac{2 m_w^* E}{\hbar^2} + \frac{V_o - E}{\hbar^2} = \frac{2 m_w^* V_o}{\hbar^2}
\]

\[
\left( \frac{\alpha L}{2} \right)^2 + \left( \frac{\beta' L}{2} \right)^2 = \frac{2 m_w^* V_o \left( \frac{L}{2} \right)^2}{\hbar^2} = R^2
\]

This is the equation of a circle with radius \(R\) in the plane defined by \((\alpha L/2)\) and \((\beta' L/2)\)! \(R\) is determined by the potential well height, QW width, and the QW effective mass! The solutions of \(\alpha\) and \(\beta'\) can be obtained graphically.
Finite Square Well (5)

One can also calculate the energy eigenvalues numerically from \( \alpha \). Let \( \beta^* \) be replaced by

\[
\left( \frac{\beta^* L}{2} \right)^2 = R^2 - \left( \frac{\alpha L}{2} \right)^2
\]

in the tangent equation. The equation becomes a function of \( \alpha \) only.

\[
f(\alpha) = \sqrt{\frac{m_b^*}{m_w^*}} \left( \frac{\alpha L}{2} \right) \tan \left( \frac{\alpha L}{2} \right) = \sqrt{R^2 - \left( \frac{\alpha L}{2} \right)^2}
\]

Once \( \alpha \)'s are determined, the energy eigenvalues can be calculated.

\[
\alpha_n = \sqrt{\frac{2m_w^*}{\hbar^2}} E_n \quad \text{and} \quad E_n = \frac{\alpha_n^2 \hbar^2}{2m_w^*}
\]

The form of this result is similar to the solution of an ideal QW. Nevertheless, the tangent equation has been modified by effective masses of the QW and barrier layers.

For comparison, the solution of an ideal QW is shown below.

\[
\xi \tan \xi = \sqrt{r^2 - \xi^2} \quad \text{and} \quad \xi = k_{0n} \left( \frac{L}{2} \right)
\]

\[
k_{0n} = \sqrt{\frac{2mE_n}{\hbar^2}}; \quad r^2 = \frac{2mV_0}{\hbar^2} \left( \frac{L}{2} \right)^2
\]
Agenda for Next Class

- Hole Energies
- Strained Wells
- Superlattices and Minibands
Thank You!
## Final Exam

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Periodic Table of the Elements

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

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<tr>
<td>ZnS</td>
<td>3.5</td>
</tr>
<tr>
<td>MgS</td>
<td>3.0</td>
</tr>
<tr>
<td>MgSe</td>
<td>2.5</td>
</tr>
<tr>
<td>MgTe</td>
<td>2.0</td>
</tr>
<tr>
<td>InN</td>
<td>1.7</td>
</tr>
<tr>
<td>CdSe</td>
<td>1.8</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.5</td>
</tr>
<tr>
<td>InP</td>
<td>1.3</td>
</tr>
<tr>
<td>AlSb</td>
<td>1.2</td>
</tr>
<tr>
<td>CdTe</td>
<td>1.1</td>
</tr>
<tr>
<td>Ge</td>
<td>0.7</td>
</tr>
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</table>

```

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

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org
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
• 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>
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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: