ECE 340
Solid State Electronic Devices

M,W,F 12:00-12:50 (X), 2015 ECEB
Professor John Dallesasse
Department of Electrical and Computer Engineering
2114 Micro and Nanotechnology Laboratory
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E-mail: jdallesa@illinois.edu
Office Hours: Wednesday 13:00 – 14:00
Today’s Discussion

• p-n Junctions
• Assignments
• Topics for Next Lecture
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**Subject to Change**
Equilibrium Condition
In equilibrium, there is no net current flow across the junction, so:
- \( J_p(\text{Drift})+J_p(\text{Diffusion})=0 \)
- \( J_n(\text{Drift})+J_n(\text{Diffusion})=0 \)

The electric field balances the diffusion current.

The potential difference \( V_o = V_n - V_p \) develops in the direction opposite to the electric field \( E \).

\( V_o \) is the “contact potential” which is a built-in potential barrier.
- Contact potential cannot be measured.

\( W \) is the “transition region”.
- Also called “depletion region” and “space charge region”.

We can calculate \( V_o \) from the separation in the Fermi levels (this will be shown later).
Contact Potential
Derivation of Contact Potential

In Equilibrium, there is no net current flow:

\[ J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p \frac{dp(x)}{dx} = 0 \]

so \( \frac{\mu_p}{D_p} \mathcal{E}(x) = \frac{1}{p(x)} \frac{dp(x)}{dx} \)

but since \( \frac{D}{\mu} = \frac{kT}{q} \) and \( \mathcal{E}(x) = -\frac{d\mathcal{V}(x)}{dx} \)

we have \(-\frac{q}{kT} \frac{d\mathcal{V}(x)}{dx} = \frac{1}{p(x)} \frac{dp(x)}{dx} \)

This is integrated over the limits \( \mathcal{V}_p \) to \( \mathcal{V}_n \) and \( p_p \) to \( p_n \)

across the space charge region:

\[-\frac{q}{kT} \int_{\mathcal{V}_p}^{\mathcal{V}_n} d\mathcal{V} = \int_{p_p}^{p_n} \frac{1}{p} dp \]

so \(-\frac{q}{kT} (\mathcal{V}_n - \mathcal{V}_p) = \ln p_n - \ln p_p = \ln \frac{p_n}{p_p} \)

so \( \mathcal{V}_n - \mathcal{V}_p = V_o = -\frac{kT}{q} \ln \frac{p_n}{p_p} = \frac{kT}{q} \ln \frac{p_p}{p_n} = \frac{kT}{q} \ln \left(\frac{N_a}{n_i^2 / N_d}\right) = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2} \)

Since \( V_o = \frac{kT}{q} \ln \frac{p_p}{p_n} \) and \( p_p n_p = n_i^2 = p_n n_n \), \( \frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_o / kT} \)
Carrier Concentrations

\[
\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_o/kT}
\]

\[
p_p = p_n e^{qV_o/kT}
\]

\[
n_p = n_n e^{-qV_o/kT}
\]

\[
p_n = p_p e^{-qV_o/kT}
\]

\[
n_n = n_p e^{qV_o/kT}
\]
Calculation of Contact Potential

**Method 1:**
- Use the relationship we derived last time

\[
V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n} = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}
\]

**Method 2:**
- Calculate the separation between the Fermi level and the intrinsic level on both sides of the junction, and sum the results

\[
E_{ip} - E_F = kT \ln \frac{p_p}{n_i}
\]
\[
E_F - E_{in} = kT \ln \frac{n_n}{n_i}
\]
\[
V_0 = (E_{ip} - E_F) + (E_F - E_{in})
\]
\[
= kT \ln \frac{p_p}{n_i} + kT \ln \frac{n_n}{n_i}
\]
Example: Contact Potential Calculation

**Method 1:**

\[
V_o = \frac{kT}{q} \ln \frac{p_{po}}{n_{no}} = \frac{kT}{q} \ln \frac{n_{no}}{n_{po}}
\]

\[
V_o = 0.026V \left( \ln \frac{10^{17}}{2.25 \times 10^4} \right) = 0.754V
\]

**Method 2:**

\[
E_{fn} - E_{in} = kT \ln \frac{n_{no}}{n_i}
\]

\[
= 0.026eV \left( \ln \frac{10^{16}}{1.5 \times 10^{10}} \right)
\]

\[
E_{fn} - E_{in} = 0.347eV
\]

\[
E_{ip} - E_{fp} = kT \ln \frac{p_{po}}{n_i}
\]

\[
= 0.026eV \ln \frac{10^{17}}{1.5 \times 10^{10}}
\]

\[
E_{ip} - E_{fp} = 0.407eV
\]

\[
qV_0 = 0.407 + 0.347eV = 0.754eV
\]

\[
V_0 = 0.754V
\]
Equilibrium Fermi Levels
• In equilibrium, the Fermi level is flat
• The equilibrium energy band separation is “q” times the contact potential
• The contact potential is a built-in potential barrier – don’t think of this as an external voltage that appears across the device
Since $p_n$ and $p_p$ are given by their equilibrium values away from the depletion (transition) region:

$$e^{qV_o/kT} = \frac{p_p}{p_n} = \frac{N_v e^{-(E_{Fp} - E_{vp})/kT}}{N_v e^{-(E_{Fn} - E_{vn})/kT}}$$

so:

$$e^{qV_o/kT} = e^{(E_{Fn} - E_{vn})/kT} e^{(E_{vp} - E_{Fp})/kT}$$

and, since $E_{Fn} = E_{Fp}$:

$$qV_o = E_{vp} - E_{vn}$$

The band separation is "q" times the contact potential.

$\Rightarrow$ Applying an external bias raises or lowers the potential barrier created by the contact potential!
Externally Applied Potentials:
A Preview
Changing the Potential Barrier

Apply Positive Voltage to p-side

Apply Negative Voltage to p-side
Space Charge at the Junction
Establishing Equilibrium

- When the materials are “joined” diffusion occurs across the metallurgical junction.
- Carriers that diffuse across the junction become minority carriers and recombine.
- The density of free majority carrier electrons and holes becomes lower than the ionized impurity concentration near the metallurgical junction, and a field begins to form.
- The field causes a drift current to form that is in the opposite direction of the diffusion current.
- Equilibrium is re-established when drift exactly balances diffusion.
\[ |Q_+| = |Q_-| \]

\[ Q_+ = qA x_{n0} N_d \]

\[ Q_- = -qA x_{p0} N_a \]
The Transition Region

- Within the depletion region, there are very few free carriers.
- The electric field within the depletion region sweeps out any carriers which enter.
- The charge density is $q$ times the number of uncompensated donors or acceptors.
- The transition width is determined by the relative concentrations.
- The assumption of depletion within $W$ and neutrality outside of $W$ is the “depletion approximation.”
Depletion Approximation:

\[ Q^+ = |Q^-| \]

\[ qN_d^+ A_{x_{no}} = qN_a^- A_{x_{po}} \]

\[ N_d^+ x_{no} = N_a^- x_{po} \]

\[ x_{no} + x_{po} = W \]

- The depletion approximation states that carriers are depleted within the depletion width “W” and that charge neutrality applies outside of the depletion region.
Reminder: Gauss’ Law

\( \nabla \cdot \mathbf{D} = \rho \) or \( \oint \mathbf{E} \cdot d\mathbf{A} = \frac{Q}{\varepsilon} \)

\( \rho \) is the charge density with units of \( \frac{\text{Coulombs}}{m^3} \)

- The divergence of the electric displacement flux density is equal to the charge density
- Can be derived from Ampere’s Law using the Continuity Equation

http://www.ibiblio.org/links/devmodules/Gauss/graphics/blob1.gif
Poisson's Equation

Apply Gauss's Law:
\[ \epsilon \oint_s \mathbf{E} \cdot dS = \sum_i q_i \]

For a small volume \( \Delta x \cdot A \):
\[ \epsilon \cdot \Delta \mathbf{E} \cdot A = q \left[ p + N_d^+ - n - N_a^- \right] \cdot A \cdot \Delta x \]

\[ \frac{\Delta \mathcal{E}}{\Delta x} = \frac{q}{\epsilon} \left[ p + N_d^+ - n - N_a^- \right] \]

\[ \lim_{x \to 0} \frac{\Delta \mathcal{E}}{\Delta x} = \frac{d\mathcal{E}(x)}{dx} = \frac{q}{\epsilon} \left[ p + N_d^+ - n - N_a^- \right] \]

Poisson's Equation:
\[ \frac{d\mathcal{E}(x)}{dx} = \frac{q}{\epsilon} \left[ p + N_d^+ - n - N_a^- \right] \]
Calculation of Electric Field: n-Side

n-side of pn junction \((0 < x < x_{no})\):

\[ p \approx 0, \ n \approx 0, \ N_a^{-} \approx 0, \ \frac{d\mathcal{E}(x)}{dx} = \frac{q}{\varepsilon} \left[ N_d^{+} \right] \]

\[ \int_{\mathcal{E}_o}^{x_{no}} d\mathcal{E}(x) = \frac{q}{\varepsilon} \left[ N_d^{+} \right] \int_{0}^{x_{no}} dx \]

\[ [0 - \mathcal{E}_o] = \frac{q}{\varepsilon} \left[ N_d^{+} \right] [x_{no} - 0] \]

\[ \mathcal{E}_o = -\frac{q}{\varepsilon} \left[ N_d^{+} \right] x_{no} \]

To determine the value \(\mathcal{E}(x)\):

\[ \int_{\mathcal{E}(x)}^{0} d\mathcal{E}(x) = \frac{q}{\varepsilon} \left[ N_d^{+} \right] \int_{x}^{x_{no}} dx \]

\[ \mathcal{E}(x) = -\frac{q}{\varepsilon} \left[ N_d^{+} \right] (x_{no} - x) \]

Maximum Value of Electric Field:

\[ E_o = -\frac{q}{\varepsilon} N_d x_{n0} = -\frac{q}{\varepsilon} N_a x_{p0} \]
Calculation of Electric Field: p-Side

p-side of pn junction \((-x_{po} < x < 0)\):

\[ p \approx 0, \ n \approx 0, \ N_d^+ \approx 0, \ \frac{d\mathcal{E}(x)}{dx} = -\frac{q}{\varepsilon} \left[ N_a^- \right] \]

\[ \mathcal{E}_o \left[ \int_{-x_{po}}^{0} d\mathcal{E}(x) \right] = -\frac{q}{\varepsilon} \left[ N_a^- \right] \]

\[ \mathcal{E}_o = -\frac{q}{\varepsilon} \left[ N_a^- \right] x_{po} \]

To Determine \( \mathcal{E}(x) \):

\[ \int_{0}^{x} d\mathcal{E}(x) = -\frac{q}{\varepsilon} \left[ N_a^- \right] \int_{-x_{po}}^{x} dx \]

\[ \mathcal{E}(x) = -\frac{q}{\varepsilon} \left[ N_a^- \right] (x_{po} + x) \]

Maximum Value of Electric Field:

\[ E_o = -\frac{q}{\varepsilon} N_d x_{n0} = -\frac{q}{\varepsilon} N_a x_{p0} \]
Assignments
Assignments

• Read info packet – key course policies and schedule are outlined here, including hourly exam dates

• Homework assigned every Friday, due following Friday

• Reading from Streetman’s book:
  – Wed 1/31: §'s 3.3.1, 3.3.2
  – Fri 2/2: §'s 3.3.1, 3.3.2 (HW2 Due)
  – Mon 2/5: §'s 3.3.3, 3.3.4
  – Wed 2/7: § 3.4.1

• Chapter 1&2 in Pierret covers similar material
Assignments

• Read info packet – key course policies and schedule are outlined here, including hourly exam dates
• Homework assigned every Friday, due following Friday
• Reading from Streetman’s book:
  – Wed 2/7: § 3.4.1
  – Fri 2/9: §'s 3.4.2, 3.4.3 (HW3 Due)
  – Mon 2/12: § 3.5
  – Wed 2/14: §'s 4.1, 4.3.1
• Chapters 1-3 in Pierret covers similar material
Assignments

• Read info packet – key course policies and schedule are outlined here, including hourly exam dates

• Homework assigned every Friday, due following Friday

• Reading from Streetman’s book:
  – Fri 2/16: §'s 4.3.1, 4.3.3 (HW4 Due)
  – Mon 2/19: §’s 4.3.3, 4.3.4
  – Wed 2/21: §'s 4.4, 4.4.1, 4.4.2
  – Fri 2/23: §'s 4.4.2, 4.4.3 (HW5 Due)

• Chapter 3 in Pierret covers similar material
Assignments

• Homework assigned every Friday, due following Friday

• Reading from Streetman’s book:
  – Wed 2/21: §'s 4.4, 4.4.1, 4.4.2
  – Fri 2/23: §'s 4.4.2, 4.4.3 (HW5 Due)
  – Wed 2/28: § 4.4.4
  – Fri 3/2: §'s 5.1 (read), 5.2, 5.2.1, 5.2.2

• Chapters 3, 4, and 5 in Pierret cover similar material
Topics for Next Lecture
• pn Junctions
Thank You for Listening!
By the time of exam No. 1 (after 17 lectures), the students should be able to do the following:
1. Outline the classification of solids as metals, semiconductors, and insulators and distinguish direct and indirect semiconductors.
2. Determine relative magnitudes of the effective mass of electrons and holes from an E(k) diagram.
3. Calculate the carrier concentration in intrinsic semiconductors.
4. Apply the Fermi-Dirac distribution function to determine the occupation of electron and hole states in a semiconductor.
5. Calculate the electron and hole concentrations if the Fermi level is given; determine the Fermi level in a semiconductor if the carrier concentration is given.
6. Determine the variation of electron and hole mobility in a semiconductor with temperature, impurity concentration, and electrical field.
7. Apply the concept of compensation and space charge neutrality to calculate the electron and hole concentrations in compensated semiconductor samples.
8. Determine the current density and resistivity from given carrier densities and mobilities.
9. Calculate the recombination characteristics and excess carrier concentrations as a function of time for both low level and high level injection conditions in a semiconductor.
10. Use quasi-Fermi levels to calculate the non-equilibrium concentrations of electrons and holes in a semiconductor under uniform photoexcitation.
11. Calculate the drift and diffusion components of electron and hole currents.
12. Calculate the diffusion coefficients from given values of carrier mobility through the Einstein’s relationship and determine the built-in field in a non-uniformly doped sample.

https://my.ece.illinois.edu/courses:description.asp?ECE340
By the time of Exam No.2 (after 32 lectures), the students should be able to do all of the items listed under A, plus the following:

13. Calculate the contact potential of a p-n junction.
14. Estimate the actual carrier concentration in the depletion region of a p-n junction in equilibrium.
15. Calculate the maximum electrical field in a p-n junction in equilibrium.
16. Distinguish between the current conduction mechanisms in forward and reverse biased diodes.
17. Calculate the minority and majority carrier currents in a forward or reverse biased p-n junction diode.
18. Predict the breakdown voltage of a p+-n junction and distinguish whether it is due to avalanche breakdown or Zener tunneling.
19. Calculate the charge storage delay time in switching p-n junction diodes.
20. Calculate the capacitance of a reverse biased p-n junction diode.
21. Calculate the capacitance of a forward biased p-n junction diode.
22. Predict whether a metal-semiconductor contact will be a rectifying contact or an ohmic contact based on the metal work function and the semiconductor electron affinity and doping.
23. Calculate the electrical field and potential drop across the neutral regions of wide base, forward biased p+-n junction diode.
24. Calculate the voltage drop across the quasi-neutral base of a forward biased narrow base p+-n junction diode.
25. Calculate the excess carrier concentrations at the boundaries between the space-charge region and the neutral n- and p-type regions of a p-n junction for either forward or reverse bias.
By the time of the Final Exam, after 44 class periods, the students should be able to do all of the items listed under A and B, plus the following:

26. Calculate the terminal parameters of a BJT in terms of the material properties and device structure.
27. Estimate the base transport factor “B” of a BJT and rank-order the internal currents which limit the gain of the transistor.
28. Determine the rank order of the electrical fields in the different regions of a BJT in forward active bias.
29. Calculate the threshold voltage of an ideal MOS capacitor.
30. Predict the C-V characteristics of an MOS capacitor.
31. Calculate the inversion charge in an MOS capacitor as a function of gate and drain bias voltage.
32. Estimate the drain current of an MOS transistor above threshold for low drain voltage.
33. Estimate the drain current of an MOS transistor at pinch-off.
34. Distinguish whether a MOSFET with a particular structure will operate as an enhancement or depletion mode device.
35. Determine the short-circuit current and open-circuit voltage for an illuminated p/n junction solar cell.
Course Purpose & Objectives

• Introduce key concepts in semiconductor materials
• Provide a basic understanding of p-n junctions
• Provide a basic understanding of light-emitting diodes and photodetectors
• Provide a basic understanding of field effect transistors
• Provide a basic understanding of bipolar junction transistors
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<td>JAN 19</td>
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<td>JAN 22</td>
<td>Materials and crystal structures</td>
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<td>JAN 24</td>
<td>Bonding forces and energy bands in solids</td>
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<td>JAN 26</td>
<td>Metals, semiconductors, insulators, electrons, holes</td>
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<td>JAN 29</td>
<td>Intrinsic and extrinsic material</td>
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<td>JAN 31</td>
<td>Distribution functions and carrier concentrations</td>
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<tr>
<td>FEB 2</td>
<td>Distribution functions and carrier concentrations</td>
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<td>FEB 5</td>
<td>Temperature dependence, compensation</td>
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<td>FEB 7</td>
<td>Conductivity and mobility</td>
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<td>FEB 9</td>
<td>Resistance, temperature, impurity concentration</td>
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<td>Invariance of Fermi level at equilibrium</td>
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<td>FEB 14</td>
<td>Optical absorption and luminescence</td>
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**Subject to Change**
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<td>Metal-semiconductor junctions</td>
<td>MIS-FETs: Basic operation, ideal MOS capacitor</td>
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<td>APR 9</td>
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<tr>
<td>MOS capacitors: flatband &amp; threshold voltage</td>
<td>Review, discussion, problems <em>(4/12 exam)</em></td>
<td>MOS capacitors: C-V analysis</td>
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<td>APR 16</td>
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<tr>
<td>MOSFETs: Output &amp; transfer characteristics</td>
<td>MOSFETs: small signal analysis, amps, inverters</td>
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<td>BJT common emitter amplifier and current gain</td>
<td>Review, discussion, problem solving</td>
<td><strong>Date &amp; time to be announced</strong></td>
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**Subject to Change**
Schedule & Policies
Important Information

• Course Website:
  – [http://courses.engr.illinois.edu/ece340/](http://courses.engr.illinois.edu/ece340/)

• Download and Review Syllabus / Course Information from Website!

• Course Coordinator: Prof. John Dallesasse
  – jdallesa@illinois.edu
  – Coordinates schedule, policies, absence issues, homework, quizzes, exams, etc.

• Contact Information and Office Hours for All ECE340 Professors & TAs in Syllabus

• Lecture Slides: Click on “(Sec. X)” next to my name in instructor list

• DRES Students: Contact Prof. Dallesasse ASAP

• Textbook:
  – Additional reference texts listed in syllabus
Key Points

• Attend Class!
  – 3 unannounced quizzes, each worth 5% of your grade
  – You must take the quiz in your section
  – Excused absences must be pre-arranged with the course director
  – Absences for illness, etc. need a note from the Dean
    • See policy on absences in the syllabus

• No Late Homework
  – Homework due on the date of an excused absence must be turned in ahead of time
  – You must turn in homework in your section
  – No excused absences for homework assignments
  – Top 10 of 11 homework assignments used in calculation of course grade
    • Do all of them to best prepare for the exams!

• No Cheating
  – Penalties are severe and will be enforced

• Turn Off Your Phone
  – No video recording, audio recording, or photography
Homework

• Assigned Friday, Due Following Friday
  – Due dates shown in syllabus
• Due at Start of Class
• Follow Guidelines in Syllabus
• Peer Discussions Related to Homework are Acceptable and Encouraged
• Directly Copying Someone Else’s Homework is Not Acceptable
  – Graders have been instructed to watch for evidence of plagiarism
  – Both parties will receive a “0” on the problem or assignment
Absences

• The absence policy in the syllabus will be strictly enforced
• To receive an excused absence (quiz), you must:
  – Pre-arrange the absence with the course director (valid reason and proof required)
  – Complete an Excused Absence Form at the Undergraduate College Office, Room 207 Engineering Hall (333-0050)
    • The form must be signed by a physician, medical official, or the Emergency Dean (Office of the Dean of Students)
    • The Dean’s Office has recently put a strict policy in place (3 documented days of illness)
  – Excused quiz score will be prorated based upon average of completed scores
  – No excused absences are given for homework, but only the best 10 of 11 are used to calculate your final grade
  – Excused absences are not given for exams, except in accordance with the UIUC Student Code
    – Unexcused work will receive a “0”
• Failure to take the final will result in an “incomplete” grade (if excused) or a “0” (if unexcused)
Exams

• Exam I: Tuesday February 27\textsuperscript{th}, 7:30-8:30 pm
• Exam II: Thursday April 12\textsuperscript{th}, 7:30-8:30 pm
• Final Exam: Date/Time To Be Announced
  – Determined by University F&S
## Grading

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<th>Historical Grade Trends*</th>
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<tr>
<td></td>
<td>10 %</td>
<td>Spring 2016</td>
</tr>
<tr>
<td>Homework</td>
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<td>A’s</td>
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<tr>
<td>Quizzes</td>
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<td>Hour Exam I</td>
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<td>C’s</td>
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<tr>
<td>Hour Exam II</td>
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<tr>
<td>Final Exam</td>
<td>35 %</td>
<td>F’s</td>
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<tr>
<td>Total</td>
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*Past performance is not necessarily indicative of future results
My Recommendations

• Read the syllabus and information posted on the course website
• **Attend class** & participate
• Attend office hours (TA and Professors)
• **Read the book**
• Re-read the book
• Look at and read selected portions of the supplemental texts
• Form study groups to review concepts and discuss high-level approaches for solving homework problems
  – Don’t form study groups to copy homework solutions
• **Don’t miss any homework, quizzes, or exams**
  • It’s hard to overcome a zero
• Ask questions in class!
Instructional Objectives (1)

By the time of exam No. 1 (after 17 lectures), the students should be able to do the following:

1. Outline the classification of solids as metals, semiconductors, and insulators and distinguish direct and indirect semiconductors.
2. Determine relative magnitudes of the effective mass of electrons and holes from an E(k) diagram.
3. Calculate the carrier concentration in intrinsic semiconductors.
4. Apply the Fermi-Dirac distribution function to determine the occupation of electron and hole states in a semiconductor.
5. Calculate the electron and hole concentrations if the Fermi level is given; determine the Fermi level in a semiconductor if the carrier concentration is given.
6. Determine the variation of electron and hole mobility in a semiconductor with temperature, impurity concentration, and electrical field.
7. Apply the concept of compensation and space charge neutrality to calculate the electron and hole concentrations in compensated semiconductor samples.
8. Determine the current density and resistivity from given carrier densities and mobilities.
9. Calculate the recombination characteristics and excess carrier concentrations as a function of time for both low level and high level injection conditions in a semiconductor.
10. Use quasi-Fermi levels to calculate the non-equilibrium concentrations of electrons and holes in a semiconductor under uniform photoexcitation.
11. Calculate the drift and diffusion components of electron and hole currents.
12. Calculate the diffusion coefficients from given values of carrier mobility through the Einstein’s relationship and determine the built-in field in a non-uniformly doped sample.

Plus continuity equation, steady-state carrier injection, and diffusion length
Quiz 1 Statistics

- Average: 8.65
- Standard Deviation: 1.49
Streetman Errata (6th Edition)

- Equation 4-30: “ΔxA” not δxA
- Equation 4-33b: “τ_p” not “τ_n”