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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<td>p-n junction Fermi levels and space charge</td>
<td>MAR 7</td>
<td>Continue p-n junction space charge</td>
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<td>MAR 12</td>
<td>p-n junction current flow</td>
<td>MAR 14</td>
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<td>MAR 28</td>
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<td>Reverse-bias breakdown</td>
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**Subject to Change**
Electric Field

Continued
Calculation of Electric Field: n-Side

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

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

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

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

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

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:

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

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

\[
p \approx 0, \ n \approx 0, \ N_d^+ \approx 0, \ \frac{dE(x)}{dx} = -\frac{q}{\epsilon} [N_a^-]
\]

\[
\int_0^x dE(x) = -\frac{q}{\epsilon} [N_a^-] \int_{-x_{po}}^0 dx
\]

\[
E_o = -\frac{q}{\epsilon} [N_a^-] \ x_{po}
\]

To Determine \(E(x)\):

\[
\int_0^x dE(x) = -\frac{q}{\epsilon} [N_a^-] \int_{-x_{po}}^x dx
\]

\[
E(x) = -\frac{q}{\epsilon} [N_a^-] \ (x_{po} + x)
\]

Maximum Value of Electric Field:

\[
E_o = -\frac{q}{\epsilon} N_d x_{n0} = -\frac{q}{\epsilon} N_a x_{p0}
\]
Junction Electric Field: Summary

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

From Integrating Poisson’s Equation
Electric Field and Contact Potential

Maximum Value of Electric Field:

\[ \mathcal{E}_o = -\frac{q}{\varepsilon} N_d x_n = -\frac{q}{\varepsilon} N_a x_p \]

Relationship of Electric Field to Contact Potential:

\[ \mathcal{E}(x) = -\frac{dV(x)}{dx} \quad \text{or} \quad -V_o = \int_{-x_p0}^{x_n0} \mathcal{E}(x) \, dx \]

Since the electric field is the negative of the potential gradient at any point.

Recall that:

\[ V_o = \frac{kT}{q} \ln \frac{p_p}{p_n} = \frac{kT}{q} \ln \frac{n_n}{n_p} \]
Calculation of Depletion Width

From the previous slide:

\[ V_o = -\int_{-x_{po}}^{x_{no}} E(x) \, dx \]

So, the negative of the contact potential is the area under the \( E(x) \) versus \( x \) triangle:

\[ V_o = -\frac{1}{2} E_o \cdot W = \frac{1}{2} q N_d x_{no} W = \frac{1}{2} q N_a x_{po} W \]

Balance of Charge Requirement: \( Q_+ = |Q_-| \iff N_d x_{no} = N_a x_{po} \)

\[ x_{po} = x_{no} \frac{N_d}{N_a} \text{ and } W = x_{no} + x_{po} = x_{no} \left(1 + \frac{N_d}{N_a}\right), \]

so \( x_{no} = W \left(\frac{N_a}{N_a + N_d}\right) \)

and \( V_o = \frac{1}{2} E_o W = \frac{1}{2} \frac{q}{\varepsilon} N_a N_d W^2 \)

\[ W = \left[ \frac{2\varepsilon V_o}{q} \left(\frac{N_a + N_d}{N_a N_d}\right) \right]^{1/2} = \left[ \frac{2\varepsilon V_o}{q} \left(\frac{1}{N_a} + \frac{1}{N_d}\right) \right]^{1/2} \]
Other Useful Relationships

\[ W = \left[ \frac{2\varepsilon V_o}{q} \left( \frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2} = \left[ \frac{2\varepsilon V_o}{q} \left( \frac{1}{N_a} + \frac{1}{N_d} \right) \right]^{1/2} \]

and \( V_o = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2} \) so:

\[ W = \left[ \frac{2\varepsilon kT}{q^2} \left( \ln \frac{N_a N_d}{n_i^2} \right) \left( \frac{1}{N_a} + \frac{1}{N_d} \right) \right]^{1/2} \]

Also:

\[ x_{po} = \frac{W N_d}{N_a + N_d} = \frac{W}{1 + N_a/N_d} = \left\{ \frac{2\varepsilon V_o}{q} \left[ \frac{N_d}{N_a} \left( \frac{N_a N_d}{N_a + N_d} \right) \right] \right\}^{1/2} \]

and

\[ x_{no} = \frac{W N_a}{N_a + N_d} = \frac{W}{1 + N_d/N_a} = \left\{ \frac{2\varepsilon V_o}{q} \left[ \frac{N_a}{N_d} \left( \frac{N_a N_d}{N_a + N_d} \right) \right] \right\}^{1/2} \]
Depletion Width and Contact Potential

\[ W = \left[ \frac{2\varepsilon V_0}{q} \left( \frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2} \]

\[ x_{p0} = \frac{N_d}{N_a} x_{n0} \]

\[ x_{n0} = \frac{N_a}{N_d} x_{p0} \]

\[ x_{p0} = \left\{ \frac{2\varepsilon V_0}{q} \left[ \frac{N_d}{N_a \left( N_a + N_d \right)} \right] \right\}^{1/2} \]

\[ x_{n0} = \left\{ \frac{2\varepsilon V_0}{q} \left[ \frac{N_a}{N_d \left( N_a + N_d \right)} \right] \right\}^{1/2} \]
Abrupt Junctions
Example: Abruupt Junction

Problem:
An abrupt junction in Si has $N_a=10^{18}$ cm\(^{-3}\) acceptors on one side and $N_d=5\times10^{15}$ donors on the other.

(a) Calculate the Fermi level positions at 300 K:
\[
p_p = n_i e^{(E_i-E_F)/kT} \quad \text{so} \quad E_{ip} - E_F = kT \ln \left( \frac{p_p}{n_i} \right) = 0.0259 \ln \left( \frac{10^{18}}{1.5 \times 10^{10}} \right) = 0.467\text{eV}
\]
\[
n_n = n_i e^{(E_F-E_i)/kT} \quad \text{so} \quad E_F - E_{in} = kT \ln \left( \frac{n_n}{n_i} \right) = 0.0259 \ln \left( \frac{5 \times 10^{15}}{1.5 \times 10^{10}} \right) = 0.329\text{eV}
\]

(b) Determine the contact potential:
\[
qV_o = 0.467 + 0.329 = 0.796\text{eV}, \quad \text{so} \quad V_o = 0.796\text{V}
\]

(c) Calculate the contact potential directly:
\[
qV_o = kT \ln \frac{p_p}{p_n} = kT \ln \frac{N_a N_d}{n_i^2} = 0.0259 \ln \left( \frac{1 \times 10^{18} \times 5 \times 10^{15}}{1.5 \times 10^{10}^2} \right) = 0.796\text{eV}, \quad \text{so} \quad V_o = 0.796\text{V}
\]
Example: A abrupt Junction [2]

Problem:
An abrupt junction in Si has $N_a=10^{18} \text{ cm}^{-3}$ on one side and $N_d=5\times10^{15}$ on the other. If the junction has a diameter of 10µm:

Calculate the junction area:

$A = \pi (5 \times 10^{-4})^2 = 7.85 \times 10^{-7} \text{ cm}^2$

Assuming a junction in equilibrium at 300K, calculate the total depletion width:

$W = \left[ \frac{2\varepsilon V_o}{q} \left( \frac{1}{N_a} + \frac{1}{N_d} \right) \right]^{1/2}$

$= \left[ \frac{2(11.8)(8.85 \times 10^{-14})(0.796)}{1.6 \times 10^{-19}} \left( 10^{-18} + 2 \times 10^{-16} \right) \right]^{1/2}$

$= 0.457 \mu m$
Problem:

An abrupt junction in Si has $N_a = 10^{18} \text{ cm}^{-3}$ on one side and $N_d = 5 \times 10^{15}$ on the other. If the junction has a diameter of $10 \mu\text{m}$:

Calculate the depletion width on the n-side ($x_{no}$) and p-side ($x_{po}$):

$$x_{no} = \frac{W}{1 + N_d / N_a} = \frac{0.457}{1 + 5 \times 10^{-3}} = 0.455 \mu\text{m}$$

$$x_{po} = \frac{W}{1 + N_a / N_d} = \frac{0.457}{1 + 200} = 2.27 \times 10^{-3} \mu\text{m}$$

Calculate the charge $Q_{+}$ and plot the charge density:

$$Q_{+} = qA x_{no} N_a = qA x_{po} N_a$$

$$= (1.6 \times 10^{-19})(7.85 \times 10^{-7})(2.27 \times 10^{11}) = 2.85 \times 10^{-14} \text{ C}$$

Calculate and plot the electric field:

$$E_o = -\frac{q}{\varepsilon} x_{no} N_d = -\frac{q}{\varepsilon} x_{po} N_a$$

$$= \frac{1.6 \times 10^{-19}}{(11.8)(8.85 \times 10^{-14})}(2.27 \times 10^{11}) = -3.48 \times 10^4 \text{ V / cm}$$
pn Junctions Under Bias

A Few Comments
Electron & Hole Motion

(1) Hole diffusion
(2) Hole drift
(3) Electron diffusion
(4) Electron drift
Bias and Fermi Level Separation

- When we apply voltage we are no longer in equilibrium.
- The application of a voltage creates a difference in the electrochemical potential across the junction boundary.
- The Fermi levels become separated by an energy of “q” times the applied voltage.
- The band separation is $q(V_0 - V)$.

$$qV_0 - qV_f = qV_0 - qV_r$$
Exam Statistics

- Average (All Sections): 71.88
- Standard Deviation (All Sections): 15.44
Assignments
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
Assignments

• Homework assigned every Friday, due following Friday
• Reading from Streetman’s book:
  – Mon 3/5: §'s 5.2, 5.2.1, 5.2.2, 5.2.3
  – Wed 3/7: § 5.2.3
• Chapters 3, 4, and 5 in Pierret cover similar material
Assignments

• Homework assigned every Friday, due following Friday

• Reading from Streetman’s book:
  – Mon 3/12: §'s 5.2.3, 5.3, 5.3.1
  – Wed 3/14: § 5.3.2
  – Wed 3/16: §’s 5.3.2, 5.3.3

• Chapters 3, 4, and 5 in Pierret cover similar material
Topics for Next Lecture
Outline, 3/12/18

• Continue pn Junctions
Thank You for Listening!
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.
Instructional Objectives (2)

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.
Instructional Objectives (3)

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>Course overview</td>
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<tr>
<td>JAN 19</td>
<td>Intro to semiconductor electronics</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>FEB 12</td>
<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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<td>FEB 16</td>
<td>Generation and recombination</td>
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**Subject to Change**
## Tentative Schedule [3]

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<td>LEDs and Diode Lasers</td>
<td>Metal-semiconductor junctions</td>
<td>MIS-FETs: Basic operation, ideal MOS capacitor</td>
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<tr>
<td>APR 9</td>
<td>APR 11</td>
<td>APR 13</td>
</tr>
<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>
</tr>
<tr>
<td>APR 16</td>
<td>APR 18</td>
<td>APR 20</td>
</tr>
<tr>
<td>MOSFETs: Output &amp; transfer characteristics</td>
<td>MOSFETs: small signal analysis, amps, inverters</td>
<td>Narrow-base diode</td>
</tr>
<tr>
<td>APR 23</td>
<td>APR 25</td>
<td>APR 27</td>
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<tr>
<td>BJT fundamentals</td>
<td>BJT specifics</td>
<td>BJT normal mode operation</td>
</tr>
<tr>
<td>APR 30</td>
<td>MAY 2 (LAST LECTURE)</td>
<td>FINAL EXAM</td>
</tr>
<tr>
<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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</table>

**Subject to Change**
Schedule & Policies
Important Information

• Course Website:
  – 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 27th, 7:30-8:30 pm
• Exam II: Thursday April 12th, 7:30-8:30 pm
• Final Exam: Date/Time To Be Announced
  – Determined by University F&S
# Grading

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<th>Grading Criterion</th>
<th>Historical Grade Trends*</th>
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<tr>
<td>Homework</td>
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<tr>
<td>10 %</td>
<td>Spring 2016</td>
</tr>
<tr>
<td>Quizzes</td>
<td>A’s</td>
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<tr>
<td>15 %</td>
<td>B’s</td>
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<tr>
<td>Hour Exam I</td>
<td>C’s</td>
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<td>D’s</td>
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<tr>
<td>Hour Exam II</td>
<td>F’s</td>
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<td>20 %</td>
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<td>Final Exam</td>
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<td>35 %</td>
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<td>Total</td>
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<td>100 %</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”