ECE 340
Solid State Electronic Devices

M,W,F 12:00-12:50 (X), 2015 ECEB
Professor John Dallesasse
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2114 Micro and Nanotechnology Laboratory
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E-mail: jdallesa@illinois.edu
Office Hours: Wednesday 13:00 – 14:00
Exam I Regrade Requests

• Due Wednesday 3/12 (Today)
• Request must be written on an 8.5” x 11” sheet stapled to exam
• Do not write on the exam itself
• The purpose is to fix grading errors, not to debate points given on incorrect answers
# Final Exam Schedule

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<td>05/04/2018</td>
<td>F</td>
<td>1:30 PM</td>
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<td>1002 Electrical &amp; Computer Eng Bldg</td>
<td>Combined</td>
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<tr>
<td>ECE 340</td>
<td>ALL</td>
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<td>2015 Electrical &amp; Computer Eng Bldg</td>
<td>Conflict</td>
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Today’s Discussion

• p-n Junctions (Continued)
• Assignments
• Topics for Next Lecture
**Tentative Schedule [2]**

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<tbody>
<tr>
<td>FEB 19</td>
<td>Quasi-Fermi levels and photoconductive devices</td>
<td>FEB 21</td>
<td>Carrier diffusion</td>
<td>FEB 23</td>
<td>Built-in fields, diffusion and recombination</td>
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<td>FEB 21</td>
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<td>FEB 26</td>
<td>Review, discussion, problems <em>(2/27 exam)</em></td>
<td>MAR 2</td>
<td>p-n junctions in equilibrium &amp; contact potential</td>
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<td>FEB 23</td>
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<td>Steady state carrier injection, diffusion length</td>
<td>MAR 7</td>
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<td>MAR 5</td>
<td>p-n junction Fermi levels and space charge</td>
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<td>MAR 9</td>
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<tr>
<td>MAR 7</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 12</td>
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<td>MAR 16</td>
<td>Minority and majority carrier currents</td>
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<td>MAR 26</td>
<td>Reverse-bias breakdown</td>
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<td>Photodiodes, I-V under illumination</td>
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<td>3/19-3/23</td>
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<td><strong>Subject to Change</strong></td>
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*(Note: The dates and topics are subject to change.)*
Back to Carrier Injection
The Case We Need to Examine

\[ \delta n(x_p) = \Delta n_p e^{-x_p/L_n} \]

\[ \delta p(x_n) = \Delta p_n e^{-x_n/L_p} \]
Minority Carrier Distribution

Define new coordinate systems referenced to edges the of the depletion region ($x_{n0}$ and $-x_{p0}$).
The diffusion equation for steady-state injection can be written:

$$\delta p(x_n) = \Delta p e^{-x_n/L_p} = p_n \left( e^{qV/kT} - 1 \right) e^{-x_n/L_p}$$

similarly, for electrons as the minority carrier:

$$\delta n(x_p) = \Delta n e^{-x_p/L_n} = n_p \left( e^{qV/kT} - 1 \right) e^{-x_p/L_n}$$

where $x_n$ is referenced to the edge of depletion region on the n-side and extends in the +x direction, and $x_p$ is referenced to the edge of the depletion region on the p-side and extends in the -x direction.

Coordinate Transformation:

$$x_n = x - x_{n0}$$
$$x_p = -x - x_{p0}$$

$x_{n0}$ and $x_{p0}$ are the n and p-side depletion widths.
No Recombination in Depletion Region

Note: This assumption is not always valid.
The Ideal Diode Equation

**Hole Current**

Recall that:

\[ J_p(x) = q \frac{D_p}{L_p} \delta p(x) \]

Therefore:

\[ I_p(x_n = 0) = \frac{qAD_p}{L_p} p_n \left( e^{qV/kT} - 1 \right) \]

**Electron Current**

Recall that:

\[ J_n(x) = -q \frac{D_n}{L_n} \delta n(x) \]

Therefore:

\[ I_n(x_p = 0) = -\frac{qAD_p}{L_p} n_p \left( e^{qV/kT} - 1 \right) \]

**Total Current**

Neglecting recombination in the transition region:

\[ |I_p(x_n = 0)| = |I_p(x_p = 0)| \text{ and } |I_n(x_p = 0)| = |I_n(x_n = 0)| \]

Since \( x_p \) is defined in the -x direction:

\[ I_n(x_n = 0)_{x,\text{axis}} = -I_n(x_p = 0)_{x,\text{axis}} \]

The total current is the sum of the electron and hole currents:

\[ I = I_p(x_n = 0) + I_n(x_n = 0)_{x,\text{axis}} = I_p(x_n = 0) - I_n(x_p = 0)_{x,\text{axis}} \]

so:

\[ I = \frac{qAD_p}{L_p} \Delta p_n + \frac{qAD_n}{L_n} \Delta n_p = qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) \left( e^{qV/kT} - 1 \right) \]
A Few Points

\[ I = qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) \left( e^{\frac{qV}{kT}} - 1 \right) = I_o \left( e^{\frac{qV}{kT}} - 1 \right) \]

n-side current \hspace{1cm} p-side current
(hole diffusion) \hspace{1cm} (electron diffusion)

• The dominant current contribution comes from injection from the more heavily doped side into the more lightly doped side.

• Reducing the doping level on either side of the junction increases the minority carrier concentrations \( p_n \) and \( n_p \) which would tend to increase the current for a given voltage.

• Increasing the doping level will cause the diffusion length to decrease, which would tend to cause current to increase for a given voltage.

• An asymmetrical junction \((p^+n \text{ or } pn^+)\) will both increase the minority carrier concentration and reduce the diffusion length.
Diode Equation: Various Conditions

\[ I = I_o \left( e^{qV/kT} - 1 \right) \]

(a) \( p-n \) Junction

\[ I \approx I_o e^{qV/kT} \quad \text{for } V = V_f \]

(b) \( p^+-n \) Junction

\[ I = qA \left( \frac{D_p P_{on}}{L_p} + \frac{D_n n_{op}}{L_n} \right) \left( e^{qV/kT} - 1 \right) \]

\[ I = 0 \quad \text{for } V = 0 \]

\[ I = qA \left( \frac{D_p P_{on}}{L_p} \right) \left( e^{qV/kT} - 1 \right) \]

\[ I = qA \left[ \frac{D_n n_{op}}{L_n} \right] \left( e^{qV/kT} - 1 \right) \]

\[ I = qA \left( \frac{D_p P_{on}}{L_p} + \frac{D_n n_{op}}{L_n} \right) \left( e^{qV/kT} - 1 \right) \]
Quasi Fermi Levels in the Forward Biased Junction
Quasi Fermi Levels in the Forward-Biased Junction

\[ p(x_p = 0) \sim p_p(x_p = \infty) = p_p \]
\[ n(x_p = 0) = n_p(x_p = \infty) + \Delta n = n_p \left( e^{qV/kT} - 1 \right) \sim n_p e^{qV/kT} \]

so:

\[ pn(x_p = 0) = p_p n_p e^{qV/kT} = n_i^2 e^{qV/kT} \]

\[ pn = n_i^2 e^{(F_n - F_p)/kT} = n_i^2 e^{(qV/kT)} \]
Relationship of $p_n$ to $n_i^2$ Under Bias

On the p-side of the junction:

$$p(x_p = 0) \sim p_p(x_p = \infty) = p_p$$

$$n(x_p = 0) = n_p(x_p = \infty) + \Delta n_i = n_p \left( e^{qV/kT} - 1 \right) \sim n_p e^{qV/kT}$$

so:

$$pn(x_p = 0) = p_p n_p e^{qV/kT} = n_i^2 e^{qV/kT}$$

This expression applies at the edges of the depletion region.
Majority and Minority Currents
Electron & Hole Currents

Ideal Diode Equation

\[ I = \frac{qA}{L_p} \Delta p_n + \frac{qA}{L_n} \Delta n_p = qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) \left( e^{qV/kT} - 1 \right) \]

Defining \( I_o = qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) \), \( I = I_o \left( e^{qV/kT} - 1 \right) \)

\[ I = qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) \left( e^{qV/kT} - 1 \right) = I_o \left( e^{qV/kT} - 1 \right) \]

Current Components

Under large reverse bias \( V_r \gg \frac{kT}{q} \), \( (e^{-qV_r/kT} - 1) \approx -1 \) so

\[ I = -qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) = -I_o \]
Majority Carrier Current: n-Side

Calculation of Majority Carrier Current:

\[ I_{tot} = qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) \left( e^{qV/kT} - 1 \right) \]

\[ = I_{n} + I_{p} = I_n(x_n) + I_p(x_n) \leftarrow \text{majority carrier + minority carrier current} \]

\[ = I_n(x_n) + qA \frac{D_p}{L_p} p_n e^{-x_n/L_p} \left( e^{qV/kT} - 1 \right) \]

so:

\[ I_{n} \equiv \text{Majority Carrier Current} \]

\[ I_{p} \equiv \text{Minority Carrier Current} \]

\[ I_n(x_n) \equiv \text{Majority Carrier Current Referenced to Depletion Region Edge} \]

\[ I_p(x_n) \equiv \text{Minority Carrier Current Referenced to Depletion Region Edge} \]
Majority Carrier Current: n-Side

\[ I_{tot} = I_n(x_n) + qA \frac{D_p}{L_p} p_n e^{-x_n/L_p} \left( e^{qV/kT} - 1 \right) \]

so:

\[ I_n(x_n) = I_{tot} - I_{p_n} = \left[ qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) \left( e^{qV/kT} - 1 \right) \right] - \left[ qA \frac{D_p}{L_p} p_n e^{-x_n/L_p} \left( e^{qV/kT} - 1 \right) \right] \]

\[ = qA \left[ \frac{D_p}{L_p} \left( 1 - e^{-x_n/L_p} \right) p_n + \frac{D_n}{L_n} n_p \right] \left( e^{qV/kT} - 1 \right) \]

where \( x_n \) is the coordinate system with \( x_n = 0 \) at the edge of the n-side depletion region

Relative to the "x" coordinate system with the origin at the metallurgical junction:

\[ I_n(x) = qA \left[ \frac{D_p}{L_p} \left( 1 - e^{-(x-x_n)/L_p} \right) p_n + \frac{D_n}{L_n} n_p \right] \left( e^{qV/kT} - 1 \right) \]

where \( \bar{x}_n \) is the width of the depletion region on the n-side of the junction
Majority Carrier Current: p-Side

Calculation of Majority Carrier Current:

\[ I_{tot} = qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) \left( e^{qV/kT} - 1 \right) \]

\[ = I_{p_p} + I_{n_p} = I_n(x_p) + I_p(x_p) \quad \Leftarrow \text{majority carrier + minority carrier current} \]

\[ = I_p(x_p) + qA \frac{D_n}{L_n} n_p e^{-x_p/L_n} \left( e^{qV/kT} - 1 \right) \]

so:

\[ I_{p_p} \equiv \text{Majority Carrier Current} \]

\[ I_{n_p} \equiv \text{Minority Carrier Current} \]

\[ I_p(x_p) \equiv \text{Majority Carrier Current Referenced to Depletion Region Edge} \]

\[ I_n(x_p) \equiv \text{Minority Carrier Current Referenced to Depletion Region Edge} \]

\( x_p \) is a transformed coordinate system: \( x_p = -x - \bar{x}_p \)

where:

The "x" coordinate system is the + going system referenced to the metallurgical junction

\( \bar{x}_p \) is the p-side depletion region width
Majority Carrier Current: p-side

\[ I_{tot} = I_p(x_p) + qA \frac{D_n}{L_n} n_p e^{-x_p/L_n} \left( e^{qV/kT} - 1 \right) \]

so:

\[ I_p(x_p) = I_{tot} - I_{n_p} = \left[ qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) e^{qV/kT} - 1 \right] - \left[ qA \frac{D_n}{L_n} n_p e^{-x_p/L_n} \left( e^{qV/kT} - 1 \right) \right] \]

\[ = qA \left[ \frac{D_p}{L_p} \left( 1 - e^{-x_p/L_p} \right) p_n + \frac{D_p}{L_p} p_n \right] e^{qV/kT} - 1 \]

where \( x_p \) is the negative-going coordinate system with \( x_p = 0 \)
at the edge of the n-side depletion region

Referenced to Metallurgical Junction and + going System:

\[ I_p(x_p) = qA \left[ \frac{D_p}{L_p} \left( 1 - e^{x+\bar{x}_p/L_p} \right) p_n + \frac{D_p}{L_p} p_n \right] e^{qV/kT} - 1 \]
Drift & Diffusion in Forward Bias

Drift Dominant + Diffusion Dominant

Drift Dominant + Diffusion Dominant

\[ I_p(x_p) = \frac{qADp}{L_p} \Delta p_n e^{-x_n/L_p} \]

\[ I_n(x_n) = I - I_p(x_n) \]

Assignments
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, 3/14/18

• 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.
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.

https://my.ece.illinois.edu/courses:description.asp?ECE340
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
## Tentative Schedule [1]

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<td>JAN 22</td>
<td>Materials and crystal structures</td>
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<td>JAN 24</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>Resistance, temperature, impurity concentration</td>
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<td>FEB 12</td>
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<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**
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<td>APR 9 MOS capacitors: flatband &amp; threshold voltage</td>
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<td>APR 16 MOSFETs: Output &amp; transfer characteristics</td>
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<td>APR 23 BJT fundamentals</td>
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<td>APR 30 BJT common emitter amplifier and current gain</td>
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**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 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
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<td>Spring 2016</td>
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<td>Quizzes</td>
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<td>27 %</td>
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<td>Hour Exam I</td>
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<td>Hour Exam II</td>
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<td>Final Exam</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

https://my.ece.illinois.edu/courses/description.asp?ECE340
Quiz 1 Statistics

- Average: 8.65
- Standard Deviation: 1.49
Exam I Statistics

• Average (All Sections): 71.88
• Standard Deviation (All Sections): 15.44
• Equation 4-30: \( \Delta xA \) not \( \delta xA \)
• Equation 4-33b: \( \tau_p \) not \( \tau_n \)