ECE 340
Solid State Electronic Devices

M, W, F 12:00-12:50 (X), 2015 ECEB
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E-mail: jdallesa@illinois.edu
Office Hours: Wednesday 13:00 – 14:00
Today’s Discussion

• Crystal Growth
• Bonding and Band Formation
• Assignments
• Topics for Next Lecture
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**Subject to Change**
Epitaxial Growth
Lattice Matched Systems

Heteroepitaxy: Grown materials are lattice matched but have different properties than the substrate

![Graph showing the relationship between band gap and lattice constant for alloys in the InGaAsP and AlGaAsSb systems. The dashed vertical lines show the lattice constants for the commercially available binary substrates GaAs and InP. For the marked example of In$_x$Ga$_{1-x}$As, the ternary composition $x=0.53$ can be grown lattice-matched on InP, since the lattice constants are the same. For quaternary alloys, the compositions on both the III and V sublattices can be varied to grow lattice-matched epitaxial layers along the dashed vertical lines between curves. For example, In$_x$Ga$_{1-x}$As$_y$P$_{1-y}$ can be grown on InP substrates, with resulting band gaps ranging from 0.75 eV to 1.35 eV. In using this figure, assume the lattice constant a of a ternary alloy varies linearly with the composition x.]

• Pseudomorphic Growth: Epitaxial growth of a non lattice-matched material

Figure 1.14
Heteroepitaxy and misfit dislocations. For example, in heteroepitaxy of a SiGe layer on Si, the lattice mismatch between SiGe and Si leads to compressive strain in the SiGe layer. The amount of strain depends on the mole fraction of Ge. (a) For layer thicknesses less than the critical layer thickness, $t_c$, pseudomorphic growth occurs. (b) However, above $t_c$, misfit dislocations form at the interface which may reduce the usefulness of the layers in device applications.

Other Concepts

• **Critical Thickness:** Growth thickness above which misfit dislocations are formed

• **Strained Layer Superlattice:** A structure of alternating layers having tensile and compressive strain such that net strain balance occurs and misfit dislocations are not formed
Epitaxial Growth Methods

• Liquid Phase Epitaxy
• Vapor Phase Epitaxy
  – (Tri)Chloride & Hydride VPE
• Molecular Beam Epitaxy
• Chemical Vapor Deposition
• Metalorganic Chemical Vapor Deposition
Silicon VPE

VPE Methods
Chloride: \[ \text{SiCl}_4 + 2\text{H}_2 \rightleftharpoons \text{Si} + 4\text{HCl} \]
Silane Pyrolysis: \[ \text{SiH}_4 \rightarrow \text{Si} + 2\text{H}_2 \]

![Diagram of Si VPE reactor](http://www.hitachi-kokusai.co.jp/global/products/semicon/batch/vpe.html)

Figure 1.15

A barrel-type reactor for Si VPE. These are atmospheric pressure systems. The Si wafers are held in slots cut on the sides of a SiC-coated graphite susceptor that flares out near the base to promote gas flow patterns conducive to uniform epitaxy.

MOCVD: Early Systems
MOCVD: Today

$$(\text{CH}_3)_3\text{Ga} + \text{AsH}_3 \rightarrow \text{GaAs} + 3\text{CH}_4$$
Figure 1.16

Crystal growth by molecular beam epitaxy (MBE): (a) evaporation cells inside a high-vacuum chamber directing beams of Al, Ga, As, and dopants onto a GaAs substrate; (b) scanning electron micrograph of the cross section of an MBE-grown crystal having alternating layers of GaAs (dark lines) and AlGaAs (light lines). Each layer is four monolayers ($4 \times a/2 = 11.3\,\text{Å}$) thick. (Photograph courtesy of Bell Laboratories.)

Figure 1.17

Molecular beam epitaxy facility in the Microelectronics Research Center at the University of Texas at Austin.

Production MBE Reactor

http://www.oxfordplasma.de/systems/v150_mbe.htm
Bonding Forces and Bond Types in Solids
Bond Types

• Ionic Bonding
  – Electron transfer
  – Coulomb attraction balanced by repulsion of nuclei

• Covalent Bonding
  – Electron sharing
  – Si, Ge, C

• Mixed Ionic-Covalent Bonding
  – Electronegativity
  – Polar covalent bonds
  – GaAs, InP, GaN

• Metallic Bonding
  – Positive cores in an electron sea
  – Typical for atoms with 3 or less valence electrons

http://www.abc.net.au/science/articles/2010/04/14/2872429.htm
Population of Atomic Orbitals

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<tr>
<th>Atomic number (Z)</th>
<th>Element</th>
<th>Number of electrons</th>
<th>Shorthand notation</th>
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<tr>
<td>1</td>
<td>H</td>
<td>1</td>
<td>1s^1</td>
</tr>
<tr>
<td>2</td>
<td>He</td>
<td>2</td>
<td>1s^2</td>
</tr>
<tr>
<td>3</td>
<td>Li</td>
<td>2</td>
<td>1s^2 2s^1</td>
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<tr>
<td>4</td>
<td>Be</td>
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<td>5</td>
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<td>6</td>
<td>C</td>
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<td>1s^2 2s^2 2p^5</td>
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<td>10</td>
<td>Ne</td>
<td>2</td>
<td>1s^2 2s^2 2p^6</td>
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<tr>
<td>11</td>
<td>Na</td>
<td>1</td>
<td>[Ne] 3s^1 3p^1</td>
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<td>29</td>
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<tr>
<td>31</td>
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<tr>
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<tr>
<td>33</td>
<td>As</td>
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<td>[Ar] 4s^1 4p^1</td>
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<td>35</td>
<td>Br</td>
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<tr>
<td>36</td>
<td>Kr</td>
<td>1</td>
<td>[Ar] 4s^1 4p^1</td>
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</tbody>
</table>

The table lists the population of atomic orbitals for elements with atomic numbers from 1 to 36, including the number of electrons in each orbital and the shorthand notation.
Electronic structure and energy levels in a Si atom: (a) The orbital model of a Si atom showing the 10 core electrons ($n = 1$ and 2), and the 4 valence electrons ($n = 3$); (b) energy levels in the coulombic potential of the nucleus are also shown schematically.

Orbital Wave Function Shape

http://winter.group.shef.ac.uk/orbitron/
sp³ Hybridization

- The sp³ hybrids are obtained by adding and subtracting all combination of s and p wavefunctions

\[
\psi_1 = \frac{1}{2}(\psi_s + \psi_{px} + \psi_{py} + \psi_{pz})
\]

\[
\psi_2 = \frac{1}{2}(\psi_s - \psi_{px} - \psi_{py} + \psi_{pz})
\]

\[
\psi_3 = \frac{1}{2}(\psi_s + \psi_{px} - \psi_{py} - \psi_{pz})
\]

\[
\psi_4 = \frac{1}{2}(\psi_s - \psi_{px} + \psi_{py} - \psi_{pz})
\]

http://www.ntu.ac.uk/cels/molecular_geometry/hybridization/Sp3_hybridization/index.html

Comments:
Strain distorts the bond angles
Bond angles for ammonia, etc. are slightly smaller
Energy Bands
• Streetman’s book, and this course, provide a qualitative understanding of how energy bands form
• A detailed understanding of how energy bands form is beyond the scope of this course
  – Energy bands arise as a solution to Schrödinger’s Equation when one considers the periodic potential of the lattice
  – The solution to Schrödinger’s Equation yields a relationship between electron energy and its momentum vector in the crystal
  – Similar to optical interference filters (butterfly wings) which use diffraction to produce colors, but at electron wavelengths
Bonding and Antibonding Orbitals in Hydrogen (The Simplest Bandgap)

Elemental Hydrogen: $1s^1$
Hydrogen #1: 2 states, 1 electron
Hydrogen #2: 2 states, 1 electron
$H_2$: 4 states, 2 electrons

Electron located between hydrogen atoms
Electron not located between hydrogen atoms

Figure 3.2
Linear combinations of atomic orbitals (LCAO): The LCAO when 2 atoms are brought together leads to 2 distinct “normal” modes—a higher energy antibonding orbital, and a lower energy bonding orbital. Note that the electron probability density is high in the region between the ion cores (covalent “bond”), leading to lowering of the bonding energy level and the cohesion of the crystal. If instead of 2 atoms, one brings together $N$ atoms, there will be $N$ distinct LCAO, and $N$ closely spaced energy levels in a band.

Energy Bands

- As atoms are brought together to form a solid, the forces of attraction and repulsion between atoms will find a balance at the proper inter-atomic spacing for the crystal.
- The discrete atomic energy levels form bands as the atoms are brought closer together. These bands become the conduction and valence band, separated by the forbidden gap where no electron states exist.
- Silicon Atom: \(1s^2 \ 2s^2 \ 2p^6 \ 3s^2 \ 3p^2\) (missing 4 electrons to fill outer shell)
  - Core: \(1s^2 \ 2s^2 \ 2p^6\)  Valence: \(3s^2 \ 3p^2\)

<table>
<thead>
<tr>
<th>n=3</th>
<th>Available States</th>
<th># of Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3P</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

- Assuming we have \(N\) Si atoms to form a crystal, we have \(N \times (3s^2 \ 3p^2)\) valence electrons

<table>
<thead>
<tr>
<th>n=3</th>
<th>Available States</th>
<th># of Electron</th>
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<tbody>
<tr>
<td>Total</td>
<td>(N \times 8)</td>
<td>(N \times 4)</td>
</tr>
<tr>
<td>Conduction Band</td>
<td>(N \times 4)</td>
<td>0 (at 0°K)</td>
</tr>
<tr>
<td>Valence Band</td>
<td>(N \times 4)</td>
<td>(N \times 4) (at 0°K)</td>
</tr>
</tbody>
</table>
What happens when a collection of Si atoms are brought closer together?

Energy levels in Si as a function of interatomic spacing. The core levels ($n = 1,2$) in Si are completely filled with electrons. At the actual atomic spacing of the crystal, the $2N$ electrons in the $3s$ subshell and the $2N$ electrons in the $3p$ subshell undergo sp$^3$ hybridization, and all end up in the lower $4N$ states (valence band), while the higher-lying $4N$ states (conduction band) are empty, separated by a band gap.

Individual atoms begin to “see” neighboring atoms (periodic potential), the p-orbitals no longer have degenerate energy: the interaction of the fields cause differences to develop in $p_x$, $p_y$, and $p_z$ orbitals*

*Simplified picture
• If the atomic spacing is such that there is significant overlap of the orbitals, electrons will be exchanged between adjacent atoms.
Significant wavefunction overlap between the orbitals of adjacent atoms – electrons are freely exchanged.
No sp$^3$ hybridization yet.
sp$_3$ Hybridization and Lattice Periodic Potential

sp$_3$ hybrid form, and electrons “feel” the periodic potential of the crystal lattice.
What happens when a collection of Si atoms are brought closer together?

Energy levels in Si as a function of interatomic spacing. The core levels (n = 1,2) in Si are completely filled with electrons. At the actual atomic spacing of the crystal, the 2N electrons in the 3s subshell and the 2N electrons in the 3p subshell undergo sp³ hybridization, and all end up in the lower 4N states (valence band), while the higher-lying 4N states (conduction band) are empty, separated by a band gap.

Depiction of Bands in Real Space

Increasing Electron Energy

Distance in “Device” (Real Space)

Conduction Band

Valence Band

0 Electrons (0K)
4N States

4N Electrons (0K)
4N States

Figure 3.7
Electron–hole pairs in a semiconductor.

Depictions in k-Space

Figure 3.5
Direct and indirect electron transitions in semiconductors: (a) direct transition with accompanying photon emission; (b) indirect transition via a defect level.
Assignments
Assignments

- Read info packet – key course policies and schedule are outlined here, including hourly exam dates
- Homework assigned every Friday, due following Friday
- Begin to read Chapter 1 of Streetman’s book
  - Mon 1/22 Sections 1.1, 1.2, 1.3.1, 1.4
  - I suggest reading all of Chapter 1, but only the above sections are assigned
  - Wed 1/24: Review Streetman Chapter 2
  - Wed 1/24: §'s 3.1, 3.1.1, 3.1.2
  - Fri 1/26: §'s 3.1.3, 3.2.1 (HW1 Due)
  - Mon 1/29: §'s 3.2.3, 3.2.4
- Chapter 1&2 in Pierret covers similar material, and complements Streetman for another perspective
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 1/24: Review Streetman Chapter 2
  – Wed 1/24: §'s 3.1, 3.1.1, 3.1.2
  – Fri 1/26: §'s 3.1.3, 3.2.1 (HW1 Due)
  – Mon 1/29: §'s 3.2.3, 3.2.4
  – Wed 1/31: §'s 3.3.1, 3.3.2
• Chapter 1&2 in Pierret covers similar material
Topics for Next Lecture
Outline, 1/29/18

• Atomic Bonding
• Energy Bands
• Metals, Semiconductors, and Insulators
• Electrons and Holes
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.
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.

https://my.ece.illinois.edu/courses/description.asp?ECE340
• 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 [2]

<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
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<tbody>
<tr>
<td>FEB 19</td>
<td>Quasi-Fermi levels and photoconductive devices</td>
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<tr>
<td>FEB 21</td>
<td>Carrier diffusion</td>
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<tr>
<td>FEB 23</td>
<td>Built-in fields, diffusion and recombination</td>
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<tr>
<td>Feb 26</td>
<td>Review, discussion, problems <em>(2/27 exam)</em></td>
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<tr>
<td>FEB 28</td>
<td>Steady state carrier injection, diffusion length</td>
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<td>MAR 2</td>
<td>p-n junctions in equilibrium &amp; contact potential</td>
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<td>MAR 5</td>
<td>p-n junction Fermi levels and space charge</td>
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<td>Continue p-n junction space charge</td>
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<td>Minority and majority carrier currents</td>
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<td>Reverse-bias breakdown</td>
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<td>Stored charge, diffusion and junction capacitance</td>
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<td>Photodiodes, I-V under illumination</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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<td>FINAL EXAM</td>
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<td>BJT common emitter amplifier and current gain</td>
<td>Review, discussion, problem solving</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](mailto: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^{th}, 7:30-8:30 pm
• Exam II: Thursday April 12^{th}, 7:30-8:30 pm
• Final Exam: Date/Time To Be Announced
  – Determined by University F&S
## Grading

| Grading Criterion |  
|-------------------|---|
| Homework          | 10 % |
| Quizzes           | 15 % |
| Hour Exam I       | 20 % |
| Hour Exam II      | 20 % |
| Final Exam        | 35 % |
| **Total**         | 100 % |

### Historical Grade Trends*

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<th>Spring 2016</th>
<th>Fall 2016</th>
<th>Spring 2017</th>
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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!