INTRODUCTION TO SEMICONDUCTOR DEVICE THEORY: EECS 320 FALL 2001

CLASS TIMES: Tu-Th: 9:00 — 10:30 am; EECS 1200
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Other texts will be brought to the student’s attention as needed.

OFFICE HOURS

Tu-Th 10:30 am — noon

DISCUSSION HOURS

M-W 1:30 — 2:30 pm; EECS1301

COURSE GRADING

The course will be graded according to the following weightage:

- Homework: 35 %
- Midterm: 25 %
- Finals: 40 %

MOTIVATIONS FOR THE COURSE

EECS 320 is a course that answers the *how* and *why* of semiconductor devices. These devices are the building blocks of all modern information processing systems. This semester, for the first time, we will cover EECS 320 in its new (and improved!) form. In addition to electronic devices we will also cover optoelectronic devices such as LEDs, laser diodes and detectors. Such devices are
critical in optoelectronic systems.

As electrical engineering and computer science students our profession revolves around information — information generation, information reception, information manipulation etc. The basic information processing systems catering to our ever increasing needs for information will occupy most of your lives, here at the University of Michigan, and, later in your careers. This course — EECS 320 — provides an important link in our understanding of the devices upon which these information systems are based.

Some of the courses you have taken in the EE area have invoked devices like diodes, transistors, resistors etc. These devices or circuit elements have been viewed in a black box mode. In other words, you have been given a description of the device in terms of its current-voltage relationship. What you have not seen is a microscopic view of why certain circuit elements behave the way they do. This is what we will try to understand. With the understanding developed in EECS 320 you will find it much easier to tackle your future circuit courses.

Consider the following microscopic questions:

• why do we use silicon to make a transistor (e.g. a MOSFET) and not gold?
• why do we use copper or aluminum to make connections between devices on an integrated chip and not silicon?
• why is the current-voltage relation for a metal wire described by Ohm’s law (i.e., a linear relation between current and voltage), but the current-voltage relation for a diode or a transistor is highly non-linear.
• why is a metal such a good conductor of current, but we don’t use it in any active devices like switches and logic gates?
• what do we really mean by electrons and holes? What is the real difference between an n-MOS and p-MOS?
• why can gadgets made from metals be fabricated in dirty factories, but ICs have to be made in super-clean labs?
• How does light come out of LEDs and laser diodes?
• How does light get converted into an electrical signal?

These and a host of other questions will be clear to you after you have had EECS 320. To develop a microscopic understanding of the devices we need to go inside the black box which has been the transistor or diode in your previous courses. To do this we need to learn a little bit of quantum mechanics, a little bit of how electrons respond to external forces and some simple physics of crystals. With this understanding we can start building insight into how and why devices behave the way they do.
Before launching into the microscopic view of devices, let us take a global
view of our field.

**Information Processing Systems**

Information processing systems can loosely be characterized in the cate-
gories: i) communication systems which include systems for transforming infor-
mation into a form that can be transmitted (for example converting sound to
electrical signals), systems for transmitting information and systems for receiv-
ing information; ii) computation systems which include the usual computers as
well as switching networks; iii) display systems which include display monitors
and their control. There are of course many sub-categories such as various kinds
of microwave systems, guidance systems, control systems etc.

No matter which system one is discussing, it is possible to define the under-
standing of the system at several levels. Let us examine a general structure of
the various levels:

- **Software:** At the highest level we have the software which controls the
  operation of the devices and components that make up the system. This field
  of study usually falls under the computer science auspices.

- **System Engineering:** At this next level one is interested in how the various
  components making up the system mesh with each other. The harmonious blend
  of the components is very critical for optimum system performance.

- **Component Design:** This level involves the design and fabrication of the
  circuits and other hardware components that make up the system. The expertise
  needed for this usually falls under "VLSI" design, CAD tools, as well as circuit
  fabrication.

- **Device Design/Fabrication:** At this level one is interested in building the
  devices that are used to then build the circuits used in the system. EECS 320
  is an important course to understand how the semiconductor devices work.

- **Material Technology:** At this level we are interested in knowing how mate-
  rials are fabricated, how they behave, what their response is to external stimuli
  and how this can be used to design devices. This is also an important area of
  study in EECS 320.

- **Physics of Materials:** At this fundamental level one tries to understand the
  physics behind the phenomenon that control device behavior. Questions like:
  how do electrons move in a solid; why is copper such a good conductor while
  silicon is not etc. are answered by this area of study.

**HOW DOES EECS 320 FIT IN?**

As the title of EECS suggests we will examine the operation of modern semi-
ciconductor devices. We will try to develop an understanding of the last three
levels described above starting from the most fundamental level. Thus we will
address the three areas: i) Physical properties of electronic materials; ii) Inter-
action of materials with the outside world; and iii) Use of the interactions for
designing devices that are important in information processing. Let us elaborate
a little.

According to an electrical engineer's world-view the materials available in
nature can be classified as: metals, insulators and semiconductors. Modern
electronics exploits all of these categories to build information processing
devices. As we will see during this course, materials like metals and insulators
form passive components of devices while semiconductors form the active
components. In order to understand and exploit semiconductors for devices we first
need to understand their physics.

**Physics of Electrons in Materials**

The first part of our course will revolve around developing an understanding
about these three categories of materials and answering questions like:

- why are metals such good conductors while semiconductors and insulators
  are not?
- how is it that miniscule amounts of impurities can dramatically alter the
  conductivity of semiconductors, but have no effect on metals?
- what are holes and why is it that even though electrons are negatively
  charged and are responsible for current flow, in some materials current flow
  occurs as if positively charged carriers are carrying the current?
- why can we change the conductivity of a region in semiconductors by an
  external field, but we cannot do this in metals?

Questions like these need to be answered before we can fully understand how
semiconductor devices operate.

All electronic and optoelectronic devices depend upon the way electrons inside
materials behave. To understand how electrons behave inside materials, we
need to use quantum mechanics according to which particles have a dual charac-
ter. Sometimes we can treat particles as particles and use classical physics.
For example if you were to describe the trajectory of the electrons that draw
out an image on the cathode ray tube of your PC display behave, you could use
classical physics. But if you were to describe how electrons behave in an atom
or in a solid, you need quantum mechanics and electrons must be described as
waves.

According to quantum mechanics, electrons have a wavelength given by (the
so called de-Broglie wavelength)

\[
\lambda = \frac{\hbar}{p}
\]

where \(\hbar\) is Planck’s constant and \(p\) is the electron momentum. When the important
distances in a physical problem become comparable to or smaller than \(\lambda\) we
need to use quantum mechanics. Otherwise classical physics is adequate. Usually
the wavelength of electrons is very small, say a few Angstroms \((= 10^{-10}\ m)\)
and we don’t need to worry about the wave nature of electrons. However, when
electrons are inside atoms or in solids we need quantum mechanics.
In EECS 320 we will make a very superficial use of quantum mechanics so that certain important concepts can be appreciated and certain terminologies can be established. Once this is done we will use classical physics.

**Interaction of electrons inside solids with external stimuli**

The next stage of our course will be to understand how electrons inside materials respond when they are subjected to potentials and electric fields. We will see how current flows in materials as well as the differences between a metal, a semiconductor and an insulator. The course will address important physical processes that control the operation of semiconductor devices such as $p-n$ diodes, Schottky diodes, bipolar transistors, MOSFETs, MESFETs, LEDs, laser diodes and detectors.

**Semiconductor Devices**

Finally we will study how various semiconductor devices behave and how one goes about optimizing them. This topic will form the bulk of EECS 320.

Semiconductor devices form the heart of the modern information age. They allow us to detect, amplify, store, create and manipulate information. Semiconductors and their devices have the following very interesting and useful properties:

- The conductivity of the material can be changed by up to 10 orders of magnitude — either by special fabrication processes or by applying a bias.
- By changing the conductivity of a sample by an applied bias the material can be used as a digital switch.
- It is possible to cause a small input electrical signal to produce a very large output signal. This property can be used to amplify signals and to generate high power signals.
- Semiconductor devices can be fabricated with such fine control that they can be switched in less than a nanosecond. Some devices can now be switched in picoseconds!
- Devices can be designed so that they have very low resistance to current flow in one direction but have a very high resistance if current flows in the opposite direction. Such *rectifying* devices are very useful for a number of applications.
- Semiconductor devices can be used to generate light and to detect light.

**TOPICS TO BE COVERED**

The following topics will be covered:

- We will discuss a simple classical model for electronic materials and see how it fails to explain modern solid state electronics.
- The basic quantum mechanics necessary to describe how electrons behave in atoms, free space and solids. This is important since all semiconductor devices exploit the properties of electrons to generate effects that can be used to design
devices.

We will only cover very rudimentary issues in quantum mechanics. Please make sure to attend the first few discussion sections even if you don’t have many questions since we will elaborate more on quantum mechanics in these sections.

- Bands theory of solids will be discussed briefly and a physical idea of this important subject will be developed. The concepts of conduction band, valence band, electrons, holes etc. will be developed.
  - The concept and importance of doping will be discussed.
  - The behavior of electrons inside semiconductors when a field or concentration gradient is present will be discussed.
  - The basic operation of the $p-n$ diode will be discussed.
  - The operation of light emitters (LEDs and LDs) and light detectors.
  - The operation of the Schottky barrier diode will be discussed.
  - The bipolar junction device will be discussed.
  - The Metal Semiconductor Field Effect Transistor (MESFET) will be discussed (very briefly).
  - The Metal Oxide Semiconductor Field Effect Transistor (MOSFET) will be discussed.

**PREREQUISITES**

Many important concepts that will be invoked in EECS 320 depend upon quantum mechanics. I don’t expect the students to be fluent in quantum mechanics. As such many concepts will have to be accepted by the students without fully understanding their basis. However, as much as possible we will try to develop intuitive insight into these concepts.

It is useful if you have some understanding of how to integrate, differentiate, solve simple differential equations etc.

**COMPUTER USAGE**

On the website: www.eecs.umich.edu/courses/eeecs320 there will be all the homeworks and their solutions. There are also pdf files which are copies of viewgraphs I will use from time to time in the class. You may download all this.

In addition EECS 320 will rely on the computer network. All homework and solutions information will also be on the directory:

/afs/engin.umich.edu/u/s/i/singh/eeecs320

- Every week several files will be placed on this directory which all students
will have access to. You can read and print out the files. These files will contain homework assignment for the week, solutions to the previous homework, any particular message or instructions, and a brief discussion of the topics covered during the previous week. Also if some interesting point comes up in office hour discussions I will try to “broadcast” it to all the students.

The directory eecs320 will have your homework problems and other information in the files ending with “.ps”. For example this handout is in the file called int320.ps. You can access this file by logging in at any unix station in the network and then using the change directory command to see the files in the eecs320 directory (follow the directions exactly):

```
cd /afs/engin.umich.edu/u/s/i/singh/eecs320 (return)
```

You can get a copy of any file in the eecs320 directory into your own directory “yourdir” (complete pathname) by typing

```
cp int320.ps yourdir (return)
```

To print the postscript file:

```
lpr printername int320.ps
```

where printername is the printer in the lab.

**APPROACH TO EECS320**

In this course we will cover a lot of very important and sometimes confusing concepts. To keep up with the class lectures and assignments it is suggested that students try to read in advance the topics that will be covered in the coming lecture. Starting with the second lecture I will assign sections to be read and understood as much as possible before you come to the class. I hope that this will encourage more questions from the students.

**HOMEWORK**

Every Thursday you will get a homework set (this will be placed on the directory mentioned above and the website). The homework will be due the following Thursday. Solutions to the homeworks will also be placed in the directory and the website.

**GSI**

The GSI for this course will be announced soon.