University of Central FLorida

Department of Electrical & Computer Engineering

EEE3350: Semiconductor Devices
Lecture Notes

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Topic 1: Introduction

Preface:

This and subsequent files are transcripts of Professor Chung Yong Chan's lecture notes for Semiconductor Devices; EEE3350. These lecture notes will be an overview of what is presented during the live lecture and are not a comprehensive substitute for attending the live lecture. Each "big picture" topic is divided into a respective pdf. The goal of drafting these notes is to reiterate many of the key concepts throughout this course and to provide both supplemental information and simulations. This course focuses heavily on the theory of semiconductor devices, some of which are not intuitive. Taking the time to study these various derivations and phenomena is essential to developing a true, and deep, understanding of the devices.

If there are any issues, whether it be typos, incorrect descriptions, broken links, and such please send me an email. My email is included in the cover page. The syllabus content will not be included in these notes, please refer to webcourses for that information. With that being said, let's begin the course.

What are Semiconductors?

Seemingly rhetorical, the question regarding what are semiconductors is a significant one that we need to discuss. Recall from Chemistry that the periodic table, and nearly any compound, may be divided into three types: conductors, semiconductors, and insulators. We know that conductors allow electricity to flow through them. Inversely, insulators reject this flow. So, a semiconductor must be somewhere in between a conductor and an insulator, right? Therefore, the semi in semiconductors must mean that part of the material conducts and the other part does not.

Thankfully this is not the case, conductivity is a binary property; either the material is conducting or insulating. Therefore, **a semiconductor is defined as an element, or compound, which conducts under certain conditions and insulates under other conditions.** The material is acting as either a conductor or an insulator for any given moment. This definition is necessary because semiconductor device physics delves into the Material Science domain. No longer are we working with ideal models for resistors, capacitors, and inductors. The material which composes up the device will ultimately drive its performance.

With our focus on Material Sciences, think to yourself what are some factors which may affect the conductivity of a given material? The most prevalent effect on conductivity, besides the material itself, is **temperature**. We know that as temperature decreases, the energy of atoms within the lattice must decrease. At absolute zero, it is stated that there is no motion of particles anywhere within the material. The inverse is true at high temperatures, the atoms have greater energy and hence vibrate more within the crystal lattice. Therefore, conductivity should be proportional to temperature. There are other variables affecting conductivity which we will discuss throughout the course, but the effects of temperature will always be present throughout our study.

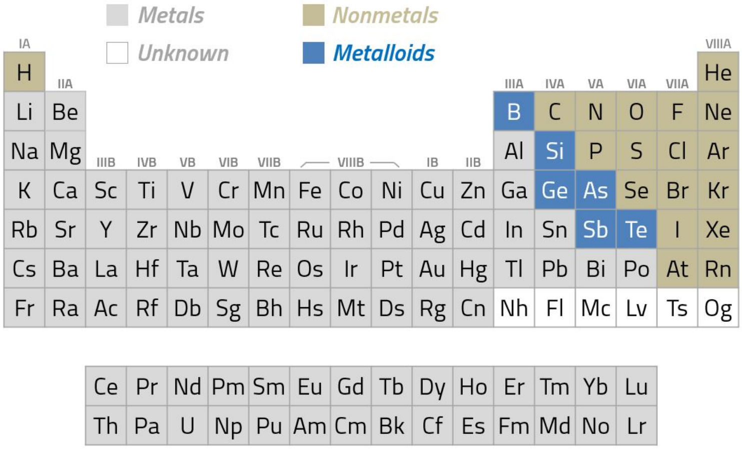

Figure 1: Periodic Table separated by conductivity (Draeger, N., PhD., 2019)

Why Study Semiconductor Devices?

1. They are the building block of modern electronics.

We promise that this class is not intended to stress you or put you through an existential crisis. We need to study Semiconductor Devices and their Physics because they are so integrated into our life. Look at anything around you, I guarantee it will have either a diode or transistor inside of it. For example, any device, or small appliance attached to a wall outlet, has a diode rectifier converting AC to DC. Within these devices are transistor counts on the order of tens to trillions. These two devices are the fundamental building blocks of modern electronics.

Provided on the following page is a figure from Wikipedia visualizing Moore's law. Moore's law states that every two years the number of transistors in an integrated circuit will double. This has slowed down in recent years, but this figure represents just a portion of the total transistors produced every year. You will study circuits containing these devices in Electronics 1 & 2, but we will study the devices from a physics-based approach.

2. They are responsible for the solid-state revolution.

Data storage is one of the fields which has benefited greatly from solid-state devices. Older technologies such as mechanical hard drives, CDs, floppy disks, and magnetic tape rely on a mechanical process to read or write data. Over time these mechanical processes will fail, potentially causing the data to be lost permanently. The advances in semiconductor devices have increased capacities, device speed, and resistance toward physical damage orders of magnitude greater than prior technology. For example, a 64 GB flash drive is very affordable, and you can drop it several times without any damage. If you dropped a mechanical hard drive the actuator or the disks could likely be damaged. With the movement toward $M\dot{2}$ drives and solid-state drives (SSDs), we can see these advancements first hand with each new generation.

To further emphasize the sheer quantity of transistors in production, each bit of Random Access Memory (RAM) in your computer has a circuit storing the bit. Depending on if the memory cell is Static RAM (SRAM) or Dynamic RAM (DRAM) cell, there are either 1 or 6 transistors needed to store each bit, respectively. This technology is based on standard memory cells circuits, but various manufacturers might have specific ways to vary this count. Regardless, an 8 gigabytes stick of DRAM would require approximately **384 billion** transistors. I hope that this emphasizes the need for nanometer-scale transistors since they are necessary to integrate so many devices into just a few integrated circuits.

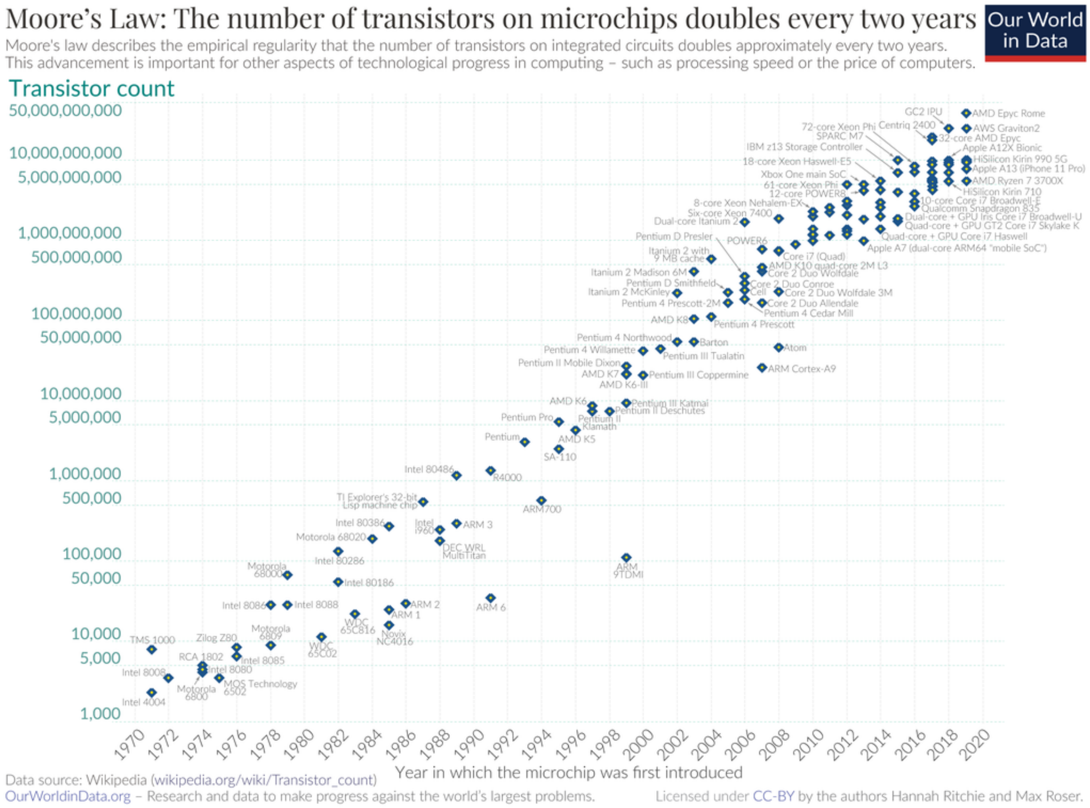

Figure 2: Moore's Law Visualization. Wikipedia contributors (2021)

New Advances in Semiconductor Devices:

This section is information I have read over the past few months. I share this in hopes to get you excited about the course and to show active research and development is going on in the field of semiconductors.

- This discovery is older, but blue Light Emitting Diodes were not available before 1990. It was with the discovery of Gallium Nitride (GaN) that true blue LEDs could be manufactured. This discovery resulted in a Nobel Prize for Professors Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura.
- The current process size has reached 5 nanometers. The process size refers to the size required to create a transistor within a semiconductor. Decreasing the process size allows more transistors to be incorporated into a given chip volume.
- Around 2016, Gallium Nitride (GaN) semiconductors have been successfully made into high efficiency power transistors for power electronics.

The Semiconductor Road Map:

With there being approximately 18 major devices, with countless variations, where should we start? The realm of semiconductor devices is broken into 4 levels:

1. Quantum

2. Device
3. Circuit
4. System

Moving down in the list above, the level of abstraction increases. The quantum level involves analyzing the semiconductor as a system where quantum mechanics cannot be ignored. Our focus will be on the device level, which contains devices such as diodes, Bipolar Junction Transistors (BJTs), and Field-Effect Transistors (FETs). The circuit-level involves creating circuits around these devices. Many semiconductor devices exhibit nonlinear behavior, hence we need to develop models which allow us to design without dealing with sets of nonlinear equations. Lastly, the system level is the most abstract, which involves the use of semiconductors as an abstract block within a system. The implementation is usually left out because the focus is on how the block interacts with the rest of the system.

Semiconductor Building Blocks:

Before we dive into the types of building blocks, we need to note that a chunk of semiconductor material can be either P or N-type. The type indicates the type of charge carrier. A P-type has a positive charge carrier, which we call holes. Similarly, an N-type has a negative charge carrier, the electron. We will delve into these types in the following lectures. As for our building, blocks we have four types:

1. P-N Junctions.

One way to view a P-N junction is by sandwiching two pieces of the **same** semiconductor material together, where one is P-type and the other is N-type. The side where the P and N-type touch forms what we call a junction. Examples of devices using P-N junctions are silicon diodes and BJTs.

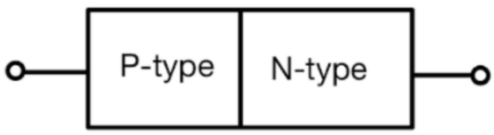

Figure 3: General structure of a P-N Junction.

2. The Metal-Semiconductor Interface (MSI)

The direct translation of MSI is a piece of metal sandwiched next to a piece of semiconductor. We know that metals are conductors, so there will be an interesting behavior at the junction, or interface, between materials. Examples of this are Gallium Arsenide (GaAs) and Aluminum Arsenide (AlAs). The most common device using this block is the Schottky Diode.

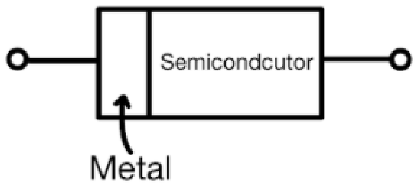

Figure 4: General structure of an MSI.

3. Heterojunctions

The root word hetero meaning different implies that we have two different materials forming the junction. Unlike P-N junctions which require the same semiconductor to be used, heterojunctions have no such restriction. For example, we could sandwich a chunk of Gallium Arsenide with Aluminum Arsenide. This block is commonly used in Solar Cells and optical applications.

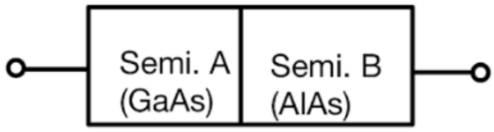

Figure 5: General structure of a Heterojunction.

4. Metal-Oxide-Semiconductor Structure (MOS)

Unlike the prior three blocks, this block has three different components. The metal and oxide are relatively fixed choice but we can use either an N or P-type for the semiconductor; allowing for many combinations to create devices. The key difference between MOS and MSI is that oxide acts as an insulator. The importance of the MOS structure cannot be emphasized enough. This type of building block dominated the design of analog integrated circuits.

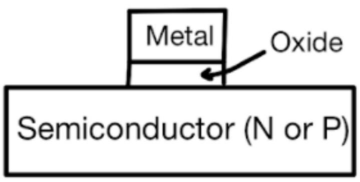

Figure 6: General structure of a MOS device.

You might note that these four types of devices are differentiated by what we sandwich together. P-N junctions are just two of the same semiconductors, whereas heterojunction can be any two semiconductors. Similarly, MSI is a combination of a semiconductor and a metal, whereas MOS has an oxide between them. Another point of differentiation is that different materials will have different properties. For example, solar cells have different properties than traditional silicon diodes.

This marks the end of the first set of notes. In the next set of notes, we will start discussing what P and N-type devices are and how they behave.

References

Draeger, N., PhD. (2019). Happy 150th birthday to the periodic table. Lam Research. https://blog.lamresearch.com/happy-150th-birthday-to-the-periodic-table/. [Online; accessed 19-August-2021].

Wikipedia contributors (2021). Moore's law. Wikipedia.https://en.wikipedia.org/w/index.php?title=Moore%27s_law&oldid=1038613038. [Online; accessed 19-August-2021].