ECE 692/599
Fundamentals of Semiconductors: Physics and Materials Properties

Taken from Yu & Cardona, Fundamentals of Semiconductors: Physics and Materials Properties

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Spring 2020
Purposes

- To prepare EE students in electronic materials and devices related research areas with adequate background knowledge in semiconductor physics and processing;
- To bridge the gap between frontier research in condensed matter physics and real-world applications in the semiconductor industry for Physics and Chemistry students; and
- To relate advanced materials research, including materials preparation and characterization techniques, to micro- and nanoelectronics for MSE students.

**Selected advance topics** (TBD by student research areas and interests: e.g. wide-band gap semiconductors for power electronics, defect engineering for memristors, first-principles methods for computational materials science or condensed matter physics, etc.)

So, let’s know each other.

**Student background survey**

Name, major, research field, advisor
Why Semiconductors?

Sometimes we say “solid state”

Image, sound, temperature, pressure, …

Information acquisition (sensors)

Information processing (Amps, A/D, processors, tranceivers…)

Information transmission (wires, busses, cables, optical fibers, or just air!)

Information processing (tranceivers, processors, …)

Displays

- Brains and muscles of the system are made of semiconductors
- Metals & dielectrics are used as transmission media
- Why?
What’s common for all the core components?

Light, sound, temperature, pressure, …

sensor

Voltage, current

Modulation of some physical quantity (output) by some others

Some kind of gain, conversion ratio, sensitivity, etc
Example: Field-Effect Transistors (FETs)
Semiconductor vs Metal

For SiO₂ dielectric, breakdown field $E_b \sim 10^7$ V/cm. No matter how thick it is, the maximum induced carrier area density is $\varepsilon_r \varepsilon_0 E_b/q = 2 \times 10^{13}$ /cm².
(Recall Gauss’s law)

For a 1 µm thick Si channel, the intrinsic carrier density $n_i = 1.45 \times 10^{10}$ /cm³, the background carrier area density is $n_i \times 10^{-4}$ cm = $1.45 \times 10^6$ /cm². (×2, considering both electrons and holes)

In principle, the area carrier density, and therefore the channel conductance, can be modulated by 7 orders of magnification!!!
Example: Field-Effect Transistors (FETs)
Semiconductor vs Metal

For SiO$_2$ dielectric, breakdown field $E_b \sim 10^7$ V/cm. No matter how thick it is, the maximum induced carrier area density is $\varepsilon_r \varepsilon_0 E_b/q = 2 \times 10^{13}$ /cm$^2$. (Recall Gauss’s law)

For a 1 $\mu$m thick Si channel, $n_i = 1.45 \times 10^{10}$ /cm$^3$, the background carrier area density is $n_i \times 10^{-4}$ cm = $1.45 \times 10^6$ /cm$^2$.

In principle, the area carrier density, and therefore the channel conductance, can be modulated by 7 orders of mag!!!

For Al, $n = 1.8 \times 10^{23}$ /cm$^3$. Even for 1 nm thin (monolayers!) Al, the background carrier area density is $1.8 \times 10^{16}$ /cm$^2$. The conductance can only be modulated by 0.1%!!!

What makes this difference?
What are semiconductors??? -- Simplified pictures

Metal: “electron gas”

https://infogr.am/how-does-bond-structure-affect-melting-point


https://keterehsky.wordpress.com/2010/03/10/9-2-semiconductor-diod/

Band picture

metal, covalent, ionic

Energy of electrons

empty, filled, Allowed states

metal, semiconductor, insulator

This line is fuzzy
What are semiconductors??? -- Simplified pictures

Metal: “electron gas”

https://infogr.am/how-does-bond-structure-affect-melting-point

NaCl

https://keterehsky.wordpress.com/2010/03/10/9-2-semiconductor-diod/


Metallic covalent ionic

Energy of electrons

Band picture

metal semiconductor insulator

This energy is called the Fermi level, Fermi energy, chemical potential. Subtle terminology differences in different fields.
What are semiconductors, anyway???

Si: $Z = 14$, $1s^2 2s^2 2p^6 3s^2 3p^2$, group IV

Al: $Z = 13$, $1s^2 2s^2 2p^6 3s^2 3p^1$, group III

To really understand the bond and band pictures of semiconductors (actually all solids), we must start from quantum mechanics. But we will first review some commonly used concepts.
What is voltage?

In electromagnetism, we were taught that the voltage is an electric potential difference.

Later, we studied semiconductor devices. Here’s what we were told:

The pn junction has a built-in “voltage” that you cannot measure with a voltmeter. If you try, the meter reads zero.

The built-in voltage, however, is an electrostatic potential difference.

Then we moved on to study the pn junction under bias. Here’s what we were told:

The voltage (applied voltage to the pn junction in a circuit) is the difference between the two Fermi levels.

What’s going on? What is voltage, after all?

Let’s do some Gedankenexperiments:

A charged capacitor, a battery.
Measure the voltage with a voltmeter.
Drive a load…
Summary & Outlook

• Semiconductors are used in active devices in information systems because they provide large modulation ranges.

• This is due to their properties derived from their chemical compositions and structures.

• We view solid-state materials from two complementary and unified perspectives: the bond picture and the band picture.

• The band picture is powerful in understanding the electrical and optical properties of semiconductors:
  • Conduction band, valence band, and the gap…
  • States are occupied by electrons up to the “Fermi level” (at zero temperature; there is a distribution at nonzero temperatures). Keep in mind terminology difference between fields.
  • We can thank the band gap for the large modulation range.

• The bond picture helps us appreciate structures, understand things like surface, interfaces, defects (increasing important in this age of nanoelectronics)

• The two pictures are unified.

• To really understand all these topics, we need quantum mechanics…

• Before we move on to quantum mechanics and solid-state physics based thereon, we will first review common concepts in semiconductor device physics, and ask questions.

• First, we re-discovered the voltage.