Semiconductors Lab- *Electrical Measurements and Inorganic Semiconductors*

Objectives Perform two fundamental kinds of electrical measurements and observe the temperature dependence of conductivity/resistivity for several materials.

Background Semiconductors are materials that display intermediate electrical properties between conductors (metals, alloys, etc) and insulators (polymers, ceramics, etc). Metals are conductive due to metallic bonding whereby free electrons can travel through the lattice and transfer energy. Insulators are non-conductive typically because in covalent bonding there are no free charge carriers. Semiconductors, on the other hand, act like a material in between these two types, having some "free charge carriers" that can either be intrinsic or extrinsic. A more specific definition can be made with respect to the material's conduction and valence bands (Figure 1).[1] A conductor has overlapping valence and conduction bands (no band gap, $\mathbf{E_g}$) while insulators have relatively large band gaps (> 4 eV). Most materials are usually classified as semiconductors if they have band gaps less than 3 eV.[2]

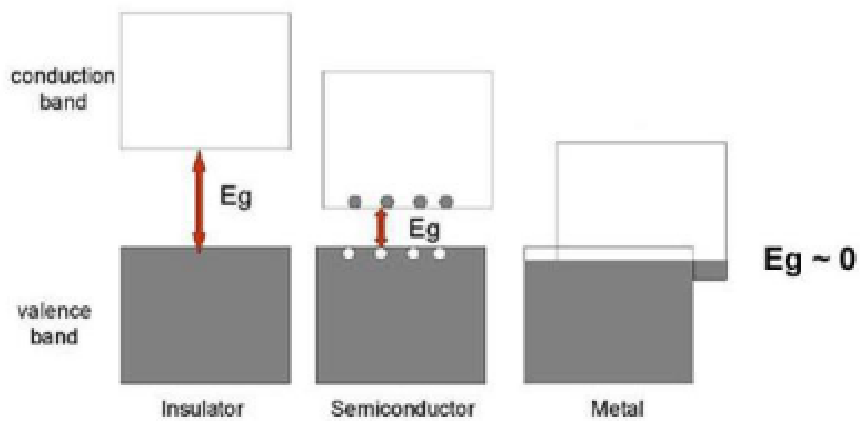

Figure 1. Defining insulators, semiconductors, and superconductors in terms of the energy difference (or overlap for conductors/metals) between their valence and conduction bands (the band gap, $\mathbf{E_g}$).[1]

One of the most important semiconductors is silicon, which is present in most semiconductor chips and transistors (and also the reason for the name "Silicon Valley"). As studied in the ceramics module, silicon is very common – it's present in sand and quartz. Silicon has four valence electrons (similar to carbon and germanium), which allows it to form a crystalline structure with covalent bonds with its neighbors. Conduction involves the flow of electrons, and although silicon looks like a metal, these covalent bonds keep electrons or charge from moving around. As temperature is increased, these bonds break, generating free electrons and increasing its conductance. Another way to achieve this is by doping the material or adding small quantities of an impurity. There are two types of impurities: n-type and p-type. N-type doping (involving arsenic or phosphorus) has 5 valence electrons, which results in an extra free electron to allow conduction (hence N for negative). P-type doping (involving boron or gallium) has 3 valence electrons, which results in holes in the lattice where electrons can move to and allow conduction (hence P for positive). Below are the corresponding band models for these two types of semiconductors (Figure 2).

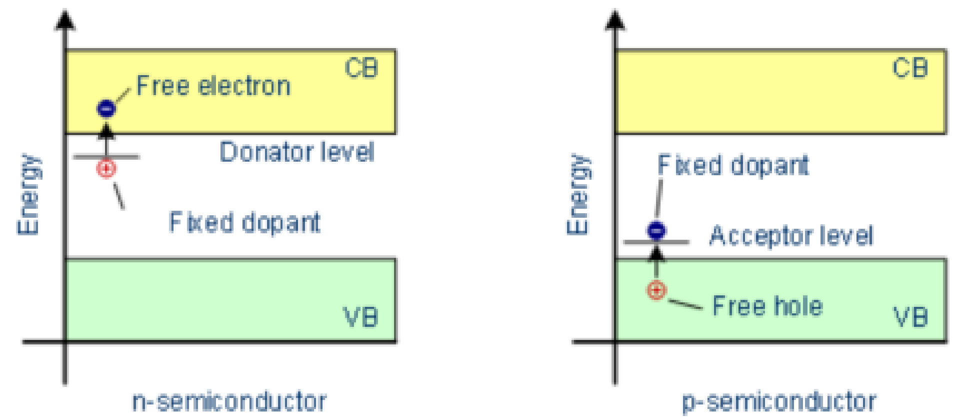

Figure 2. Band model of doped semiconductors: n-type (left) and p-type (right).[3]

How do we identify these different materials? We must first look at electrical resistance, **R = V/I** (measured in ohms, **Ω**) or reciprocally, electrical conductance, **G = 1/R = I/V** (measured in Siemens, **S**). To minimize confusion, we will use resistance and its related units instead of conductivity and its related units in this lab (however, both are often used in the field and both are correct to use). While other electrical properties can be measured (capacitance, inductance, and complex impedance), we will focus on resistance measurements as those apply to individual materials best (the others are more relevant for electronic devices, which usually involve several different materials assembled together).

To measure the electrical resistance (and the more useful geometry-corrected intensive property resistivity, **ρ = Ω*m**), we use either a relatively simple 2-point measurement or the more complicated 4-point measurement (**Figure 3** top and bottom, respectively). Usually, the simpler 2-point measurement is sufficient for most applications, but in many cases, you will encounter contact resistance (**R_{lead}** in **Figure 3**) which arises from poor electrical contact between your measuring device and sample. Likewise, many materials, such as semiconducting thin films, have large contact resistances, making the measured resistances inaccurate. To get around this, we use the more complicated 4-probe measurement (which allows us to effectively cancel out the effect of contact resistance on the applied current).

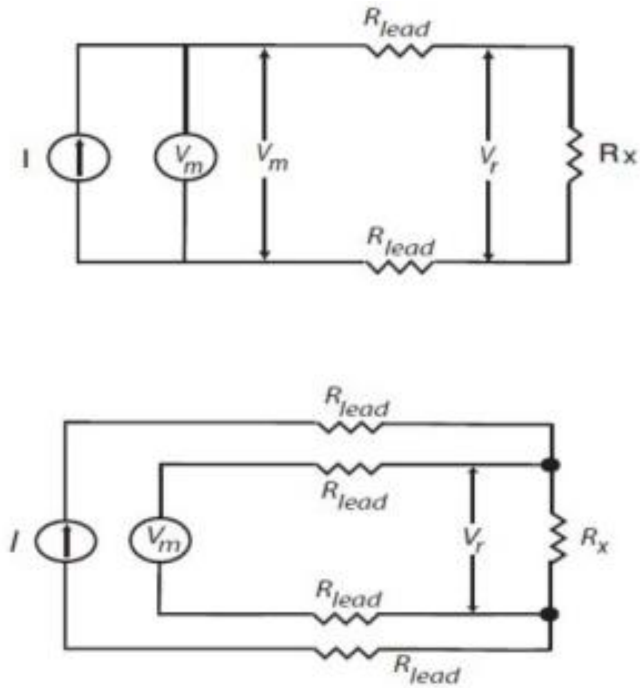

Figure 3. Circuit schematic of a 2-point resistance measurement (top) and a 4-point resistance measurement (bottom).

How does one differentiate a conductor, a semiconductor, or an insulator by electrical resistance of the material? It turns out it generally isn't practical to do this by electrical resistance alone. While the history of semiconductor science is a bit murky, one of the first and major distinctions between semiconductors and conductors was discovered by Michael Faraday in 1833.[4] While was known that conductors (like metals) experience an *increase* in resistance (they become worse conductors of charge) at higher temperatures, Faraday observed "sulphurette of silver" (silver sulfide, Ag_2S) experience a *decrease* in resistance at higher temperatures. Many other studies afterwards have shown this temperature dependence of conductivity is a key distinguishing factor between conductors and semiconductors.

In this laboratory, we will explore how we measure electrical properties of materials (specifically resistance and the related resistivity) using the "simple" 2-point and the "more complex" 4-point measurement. Additionally, we will be examining the temperature dependence of the measured resistances (and resistivity) of four different types of materials: aluminum foil, undoped silicon, n-type silicon, and p-type silicon.

Discussion

- Describe the difference between insulators, semiconductors, and conductors and how we can tell them apart through experimental measurements.
- Why do we use a 4-point measurement instead of a 2-point measurement?
- Compare the resistivity of the aluminum foil with literature. Is there a difference? Why? What is contact resistance? How might it affect your measurements?

Materials

- Aluminum foil
- Silicon
- n-type silicon
- p-type silicon

Equipment

- Multimeter with resistance measurement capabilities
- Several standard resistors with known resistance values
- PID controlled furnace (PID-200)
- Constant current source (CSS-01)
- Low current source (LCS-02)
- Digital microvoltmeter (DMV-001)
- Four probe arrangement

Experiment

Part A: Electrical resistance measurements

- Set multimeter to resistance (Ω) mode to measure resistance of some standard resistors and "corroded/bad" resistors.

Part B: Temperature Dependence of Materials/Semiconductors

- Place sample on the base plate of the four probe arrangement. Unscrew the pipe holding the four probes and let the four probes rest in the middle of the sample. Apply a very gentle pressure on the probes and tighten the pipe in this position with a screwdriver. Make sure there is good contact.
- Connect the outer pair of probes to the constant current source through the 3-pin socket and the inner pair to the DC micovoltmeter through a BNC connector.
- Place the four probe arrangement in the oven.
- Switch on the DC microvoltmeter and allow about 5 minutes for thermal stability. Zero the voltmeter with the knob.
- Switch on the constant current power supply or low current power supply and check the zero reading. Adjust if necessary again. In case it cannot be adjusted, note down the voltage and treat it as a zero error.
- Increase the current gradually and take corresponding readings of the voltage. Check Ohm's law (R=V/I). For resistive samples, choose lower currents and for conductive samples choose higher currents (why is this?). Check the voltage for at least 4 different currents.
- Measure each sample at 4-5 different temperatures (room temp to 200C). The temperature can be changed by using the PID controlled oven. Set the oven to ~10 degrees lower than the intended temperature. Allow the oven to cool when you are done (this can take some time).

References

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