MSE170 U. Washington

Fundamentals of Materials Science

Lab IV: Electrical Properties

Study Questions

1. How would the electrical conductivity of the following vary with temperature: (a) ionic solids; (b) semiconductors; (c) metals? Briefly explain your answer.

2. One deforms a copper crystal and a sodium chloride crystal at room temperature. Describe and explain the change in behavior of the electrical conductivity in both cases.

3. A diode is manufactured by diffusing phosphorus into silicon containing $10^{18}/m^3$ aluminum impurity atoms.

    - Draw a plot of the phosphorus concentration vs. distance for some time $t>0$. At what phosphorus concentration does the p-n junction appear? Indicate this on your graph.
    - After 10 minutes at 500 ºC, the p-n junction is found to be 10 μm into the material. How far will it be after 20 minutes?

4. The electrical conductivity of a metal and of a heavily doped n-type semiconductor decreases with increasing temperature. The conductivity of a narrow gap intrinsic semiconductor and an ionic conductor increases with temperature. Give explanations in 25 words or less for each of these four observations.

5. The equation for conductivity, σ, is given as $\sigma = n|q|\mu$, where n = the number of carriers, q = the charge carried by each, μ = the mobility of carriers. Use this equation to explain the following:

    - Comparison of magnitude of conductivity of metals and n-type semiconductors.
    - Temperature dependence of resistivity of semiconductors.

6. State the formula which describes how the resistivity, ρ, of a metal increases with temperature. Write a simple problem, which could be used for an examination based on this formula.

Scope

The following experiments are designed to illustrate the effect of temperature on electrical conductivity of metals and semiconductors. The intent of these experiments is to demonstrate some of the various mechanisms of electrical conductivity.

Background

The conductivity, σ, of different materials spans approximately twenty-five orders of magnitude (Figure 1). (Note: This is the largest known variation of any materials property.)

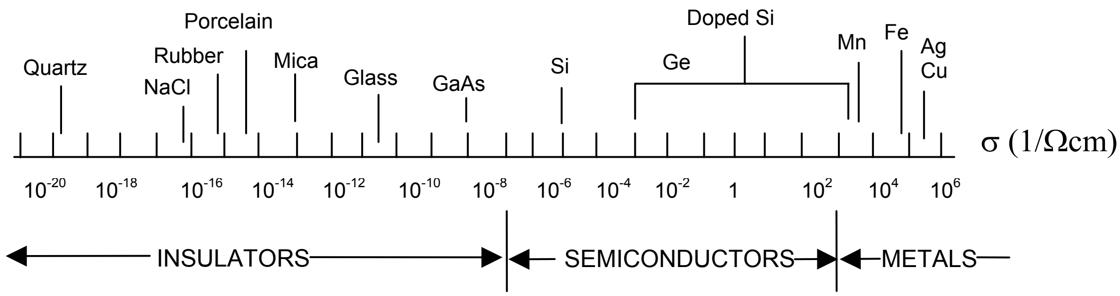


Figure 1. Room temperature conductivity of various materials. The conductivities of semiconductors varies substantially with purity and temperature.

What is an electron? To date, no one has ever seen an electron. We can only experience the effects from the actions of the electrons e.g., on a television screen or in an electron microscope. However, in each of these devices, the electron behaves differently; in the television tube the electron acts as a particle, while in the electron microscope it behaves as a wave. This effect is known as the wave-particle duality of electrons. So, simply put, an electron is a packet of energy that behaves sometimes as a particle and sometimes as a wave.

Before going on, a brief review of some of the fundamental equations pertaining to electrical conductivity,

Ohm's Law:

$$V = IR$$

where,

V = a potential difference, in volts
I = electrical current, in amps
R = electrical resistance, in ohms

The resistance of a conductor can be calculated from its physical dimensions by:

$$R = \rho L/A$$

where,

L = the length of the conductor
A = the cross sectional area of the conductor
P = the conductor's specific resistance or resistivity

By definition, resistivity is the inverse of conductivity, σ, thus:

$$P = 1/\sigma$$

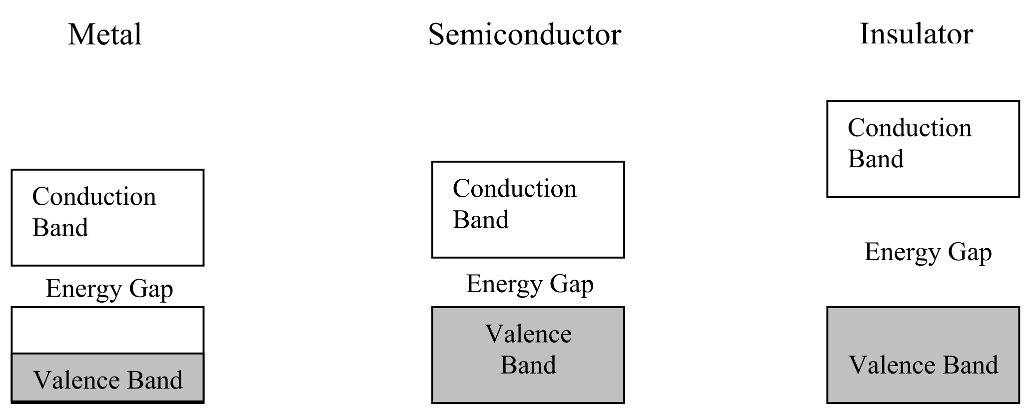
And finally,

$$\sigma = ne^2t/m$$

where,

n = the number of charge carriers (electrons or holes)
e = the charge of the carrier (1.6902×10^{-19} coulomb)
t = the mean free path or time between collisions
m = the effective mass of the charge carrier (electron = 9.11×10^{-31} kg)

Band Structure of Materials



Electrical Conductivity in Metals

For metals, it is generally accepted that the outer or valence electrons play an important role in electrical conduction. If you recall the nature of the metallic bond, the valence electrons are described as a "sea of electrons" moving freely from one atom to another. If we examine the band structure of metals we find that the valence band is only partially filled and it is these loosely bound electrons that account for the high conductivity of metals.

Previously, we discussed the duality of electrons, indicating that they can be described as either a particle or a wave. If we first consider the particle nature of an electron, one can explain the resistivity by means of collisions per unit time, the greater the number of collisions the greater the resistance. The chance of an electron colliding with an atom increases as the number of crystalline imperfections increases, these imperfections being: impurity atoms, vacancies, dislocations, grain boundaries, thermal vibrations of the atoms, etc. This concept qualitatively describes the increase in resistance with increasing cold working and alloying. It also helps explain the increase in resistance with increasing temperature: an increase in temperature causes the lattice atoms to oscillate farther from their equilibrium positions, thus increasing the chance of colliding with a drifting electron.

If we next examine the wave nature of electrons and its relation to resistance, we can visualize the lattice atoms scattering the incoming electron wave. Think of an atomic plane as the surface of a pool and the atoms as a uniform array of balls anchored to the bottom of the pool with springs. When a wave (electron) moves across the surface of the pool it contacts the balls and is broken up. Much of the energy from the wave is in the form of concentric waves. For a periodic array of atoms, the waves are scattered "in phase", meaning they constructively interfere and the original wave (electron) is transmitted across the pool surface with no loss of energy. However, if the array of balls is not uniform, i.e., some balls are larger or smaller, there are missing balls, or the array is not uniform, the re-emitted waves will not constructively interfere and a portion of the wave energy will be lost. This concept can be extended to the three dimensional solid and used to describe electrical conduction in metals.

Electrical Conductivity in Semiconductors

In semiconductors, the bonding is quiet different from that of metals. In metals, the valence electrons are loosely held by atoms and are essentially free to move from one atom to another. This type of bonding is known as metallic bonding. In semiconductors, the electrons are held more tightly and shared by two adjacent atoms. These electrons cannot freely move about. The band structure in semiconductors is also different from that of metals. In semiconductors the valence band is completely filled and there is an energy gap which must be overcome before an electron can move throughout the crystal structure. In semiconductors this gap is relatively small; the thermal energy at room temperature is generally great enough to promote electrons into the conduction band. As the temperature of the material is increased above room temperature a greater number of electrons are promoted and the resistance of the material decreases. This means that conduction is solely a result of valence electrons from that element being promoted to the conduction band and then migrating under the influence of an electric field. An extrinsic semiconductor is a material which is intentionally "doped" with atoms from an additional element. The dopant, as it is called, must be from a different column of the periodic chart as the semiconductor. The dopant atom therefore has more or less valence electrons than the semiconductor and aids in supplying electrons to the conduction band, or the creation of holes in the valence band.

Part I: Electrical Conductivity of Copper

Materials:

- Solid copper wire coil
- Liquid nitrogen with dewar
- Dry ice
- Ice water bath
- Room temp water bath
- Hot plate/ boiling water bath
- Multimeter
- Thermocouple

Procedure:

1. Using the multimeter, measure the resistance of the copper coil at room temperature. Record the reading along with the temperature and dimensions.
2. Place the coil consecutively in room temp water, ice water, dry ice, liquid nitrogen, and boiling water. Measure and record the resistance and temperature for each condition.

Questions for Consideration:

- What happened to the resistance of the wire as the temperature dropped from 100 °C to -196 °C? Why?
- What effect does cold working have on the resistance of the wire?
- Given the effect of cold working on resistance, how would the resistance change if the copper wire were a perfect (no defects) single crystal?
- What do you think would happen if the annealed copper was alloyed with another metal?

Part II: Electrical Conductivity of Silicon

Materials and Equipment:

- Electric furnace
- Multimeter
- Silicon wafer
- Wire leads

Procedure:

1. Connect the two wire leads to the HIGH and LOW input terminals on the multimeter.
2. Thread the other ends of the leads (the ends with the alligator clips) through the access hole in the top of the furnace, and into the furnace box.
3. Clip one of the two alligator clips to each end of the silicon wafer sample, and let the sample hang from the leads in the center of the furnace box.
4. The furnace is programmed to go from 100 °C to 400 °C in 50 °C steps, holding the temperature at each step for five minutes. The TA will start the furnace program.
5. When the resistance reading stabilizes at each temperature step, record the temperature and resistance values.

Questions for Consideration:

- What happened to the resistance of the Si wafer as the temperature dropped from 250 °C to 150 °C? Why?
- What effect does the temperature have on the resistance of the Si wafer?
- What effect would doping have on the resistance of the wafer?
- Why are electronic devices manufactured from single crystals? What effects would grain boundaries or dislocations have on the performance of the device.

Laboratory Report (short format)

The observations recorded in your notes during the laboratory should serve as a primary basis for your laboratory report, so you will want to work at makin clear, concis, easy-to-remember observations and sketches during the lab.

Please follow the lab report format outlined by the MSE department.

The questions included in the text of the laboratory sheet should serve as a basis for you to begin thinking about the laboratory on a more critical level. **YOU ARE NOT TO MERELY ANSWER EACH OF THE QUESTIONS ONE BY ONE IN SEQUENCE. THEY ARE TO BE INCORPORATED INTO THE WRITE UP.** By carefully considering these questions, you should begin to go beyond the surface of your observations. This in turn will help you aproach an understanding of the underlying phenomena with greater depth. In addition to the procedural portions of this laboratory, we will be looking closely at your introduction section, as well as your discussion section, and conclusions, to determine if you clearly understood the motivation behind the experiment as well as to see whether or not you are able to draw from the information presented in lecture and provided in the text in order to understand the phenomena observed.

Other things to include in your lab report:

- Plot, on the same graph, the resistance and conductance of the copper wire as a function of temperature.
- Graph the conductance of the Si wafer as a function of temperature. Comment on the slope of the curve with respect to the promotion of electrons into the conduction band.
- Discuss the differences in the mechanism of conduction of metal and semiconductors.