ADVANCED UNDERGRADUATE LABORATORY

EXPERIMENT 20

Semiconductor Resistance, Band Gap, and Hall Effect

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Introduction

Solid materials are usually classified as metals, semiconductors, or insulators. In general, metals conduct electricity better than semiconductors, and insulators essentially do not conduct electricity at all, but the critical distinguishing characteristic between the 3 classes of materials is their electronic energy structure. The basic parameters determining the conductivity of a semiconductor are the band gap, the extrinsic charge carrier densities, and the mobility of the charge carriers. The goal of this experiment is to measure these parameters for two doped germanium samples.

The allowed energies of electrons inside solid materials are quantum mechanically restricted to certain ranges known as energy bands. Lower energy bands which are completely filled are known as the valence bands; the first band which is either empty or is partially filled is known as the conduction band. The difference in energy between the top of the valence band and the bottom of the conduction band is known as the energy gap. Materials in which the highest allowed energy band is always partially filled are metals, since the partially filled conduction band allows electrons to move freely. Insulators and semiconductors are materials in which the conduction band is normally empty. In a semiconductor the energy gap is small enough that at normal temperatures some electrons have enough thermal energy to jump over the band gap to the conduction band. In an insulator the band gap is so large that the conduction band is essentially always empty. As a result, the resistivity of an insulator is very, very high.

The resistance of a semiconductor is normally several orders of magnitude higher than that of a metal, but it is the temperature dependence of the resistance which distinguishes between a metal and a semiconductor. The resistance of the **semiconductor** germanium (Ge) **decreases** with increasing temperature, whereas in a **metal** the resistance **increases** with temperature. In a metal the number of carriers is fixed, and the increase in resistance of the metal is because of the increased number of thermally excited lattice vibrations (**phonons**) from which the charge carriers can scatter. In a semiconductor the increase in scattering is overwhelmed by the exponential increase in the number of carriers, as a result of thermal excitation across the energy gap. The temperature dependence of the resistance is used to determine the band gap.

The Hall voltage is the voltage transverse to both magnetic field and current. It appears when a magnetic field transverse to the direction of current flow is applied.The sign of the Hall voltage determines whether the dominant carriers in the semiconductor are electrons or holes, and its magnitude is a measure of the carrier concentration.

Theory

Semiconductors, metals, electrolytes and other conducting materials have charge carriers that are free to move about in the substance, not being tightly bound to any particular atom or molecule. If an electric field exists in such a conducting material, positive and/or negative charge carriers tend to drift towards the electrode or contact of opposite polarity, thus causing an electric current. The charge carriers are not able to travel unimpeded from one contact to another; in a solid they collide with defects in the lattice structure such as impurity atoms and lattice vibrations, and in a liquid or gas with other ions, molecules, or atoms. These collisions impede the current flow and give rise to electrical resistance.

Conductivity

To explain the conduction processes in a semiconductor we need to assume that the electric current may be caused by the flow of two types of charged carriers, electrons and holes. The hole may be looked upon as a particle carrying a positive electronic charge and its movement is analogous to that of the gap in a line of cars as they accelerate away from a traffic light which has just turned green: as the cars (electrons) move forward in turn, the gap (hole) moves in the opposite direction. The electrical conductivity may be expressed in terms of the number of charge carriers, their charge, and their mobility; i.e., the average velocity of the carrier per unit of electric field:

$$\sigma = pe\mu_h - n(-e)\mu_e = pe\mu_h + ne\mu_e \tag{1}$$

here p/n is the carrier concentration or number of holes/electrons per unit volume, $+e$ is the hole/electron charge and μ_h/μ_e is the hole/electron mobility.

Equation (1) applies to a semiconductor when the numbers of electrons and holes present are significant. If the semiconductor is "doped" by introducing suitable impurities, the charge carriers can be made predominantly of one type. In germanium, which is in Group 4 of the periodic table, a Group 5 impurity such as antimony has an extra electron which becomes a free charge carrier and the semiconductor is then said to be n-type. Conversely, a Group 3 impurity such as indium makes germanium p-type, since the missing electron is equivalent to a hole in the valence band. Equation (1) thus becomes

$$\sigma = pe\mu_h \tag{2}$$

for a p-type semiconductor or

$$\sigma = ne\mu_e \tag{3}$$

for an n-type semiconductor.

In a pure semiconductor the number n of charge carriers per unit volume is far smaller than in a metal. For example, in pure Ge at room temperature, $n = p\infty 10^{10}$ cm ^{3}, whereas in a typical metal, $n = p\infty 10^{22}$. This results in a much larger conductivity in a metal than in a semiconductor. However as the temperature is raised the conductivity increases rapidly, whereas in metal the conductivity **decreases** slowly. This striking difference in behaviour is a direct consequence of the property of a semiconductor which distinguishes it from a metal, namely, the existence of a relatively small **energy gap** between electron states in the **valence band** (which correspond to the bound electrons constituting the covalent bonds between the atoms) and electron states in the **conduction band** (which correspond to electrons free to conduct electricity). At low temperatures, all the electrons are in the valence band which is completely full (corresponding to the saturation of the 4 covalent bonds by the 8 electrons available from each Ge atom of valence 4 and its 4 nearest neighbours), so that there are no free charges or carriers. As the temperature T is raised, thermal excitation of electrons occurs across the energy gap of width _E and the number of free electrons *n* in the conduction band and the equal number *p* of free holes in the valence band increases according to the expression

$$n_i = p_i = AT^{3/2}e^{-\Delta E/(2k_B T)} \tag{4}$$

The derivation of this equation is given in Kittel p. 367, but we can understand the origin if the exponential term, which dominates the much less rapidly varying temperature dependence due to the $T^{3/2}$ term, by comparing it with the corresponding Boltzmann factor, $e^{-\Delta E/2k_B T}$ for the probability of occupation of two states separated by energy ΔE.

At high temperatures, the temperature dependence of the conductivity is largely determined by the exponential term in equation (4), since the mobilities in equation (1) vary only as a power law of the temperature [see Adler (1964)]. At low temperatures, the conductivity of a doped semiconductor stops decreasing exponentially with decreasing temperature (intrinsic behaviour) when the numbers of carriers from equation (4) become roughly equal to the number of charge carriers contributed by the impurities. At lower temperatures the conductivity depends only on the variation in the mobilities (extrinsic behaviour).

Hall Effect

Consider the sample of p-type semiconductor with current density J_x flowing in the x-direction. In the presence of a magnetic field B_0 along the z-direction, the holes will experience a force (the Lorentz force) driving them towards the bottom of the sample as shown in Figure 1.

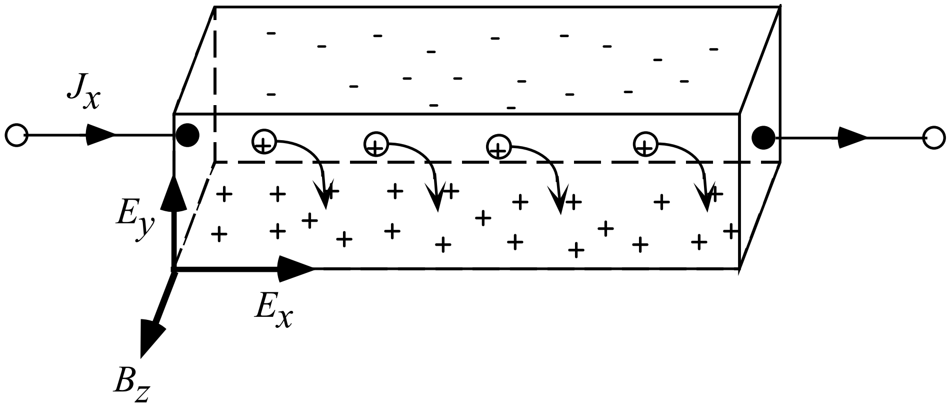

Figure 1: The Hall effect for positive charge carriers.

This net charge displacement results in the bottom surface becoming positively charged and the top surface becoming negatively charged. This process obviously cannot continue indefinitely since it would generate an infinite field in the y-direction. What happens is that the electric field E_y adjusts itself so that the force on the holes due to this field exactly cancels the Lorentz force.

i.e.

$$eE_y - = ev_x B_z \tag{5}$$

where υ_x is the hole velocity. Now

$$J_x - = epv_x \tag{6}$$

so that

$$E_y = J_x B_z / ep \tag{7}$$

or

$$R_H - = E_y / J_x B_z - = 1/ep \tag{8}$$

where R_H is the Hall coefficient. In a similar manner it can be shown that for an n-type semiconductor, in which the charge carriers are electrons with charge -*e*, the Hall coefficient is

$$R_H - = 1/(-e)n = -1/en \tag{9}$$

Note especially that the Hall coefficient has opposite signs for n and p-type semiconductors. The carrier concentration p or n can be determined from equations (8) or (9), and when combined in equation (2) with the measured conductivity, the carrier mobility μ_h or μ_e can be determined.

In any real semiconductor, both holes and electrons contribute to the conductivity. If one type of carrier is dominant, it is called the majority carrier and the other type is referred to as the minority carrier. The contribution to the conductivity from minority carriers cannot always be neglected, and may need to be included in your analysis.

Experiment

The dimensions of the samples of n and p-type Ge are shown in Figure 2. The lead marked 2 is at the end of the probe farthest away from the plug. Two pairs of contacts are used to measure the resistivity,[1] since the voltage across the current pair (1,2) would include the contact resistances.

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[1] This is known as the “4-probe method”.

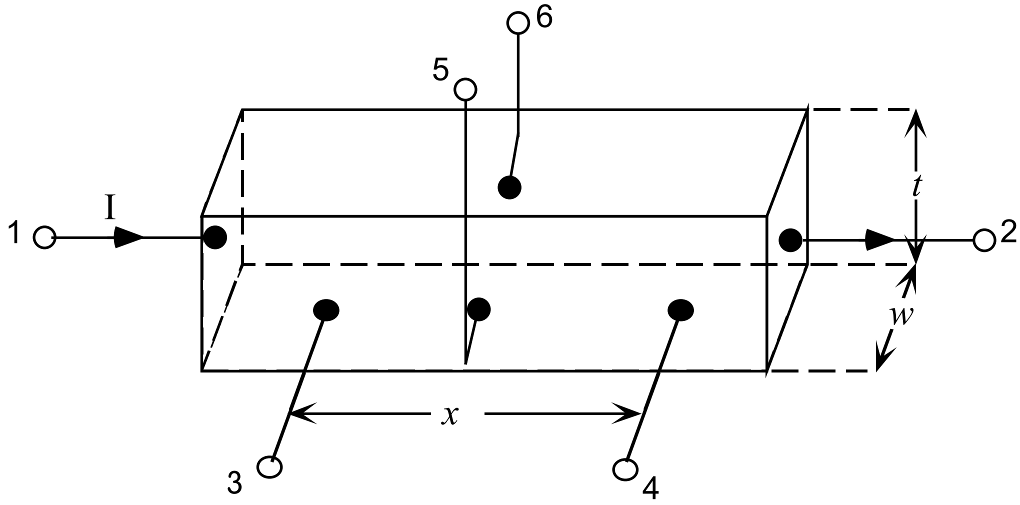

Figure 2: Physical Dimensions and Contacts for Ge Samples.

Contacts	Dimensions
(1,2) current	t = 0.11 cm
(3,4) resistive voltage V_R	x = 0.57 ± 0.03 cm
(5,6) Hall voltage V_H	w = 0.11 cm

Hall Coefficient

Measure the Hall voltage of both samples at room temperature at several current settings using the permanent magnet. The current should not exceed ±4*mA*. The Hall coefficient can be deduced by making an appropriate least squares fit.

You will have to cope with the problem that a small voltage typically exists between the Hall contacts 5 and 6 even in zero magnetic field. Note that this apparent Hall voltage is a function of current through the sample. It has been observed that the magnitude of this response is much greater in the B-type probes than in the A-type. It has also been observed that the response may be quite different between individual A or B probes. You may wish to study these relationships in the absence of magnetic fields but the important considerations for this experiment is that this "background" Hall voltage be removed from your true Hall voltage measurements. You can eliminate this residual voltage using any of three methods; all of which should yield the same results within errors. These are:

A. A balancing potentiometer circuit can be attached to contacts 3 and 4. The potentiometer should be adjusted so that the voltage between the contact 6 and the potentiometer is zero over the full range of current up to 4 *mA*.

B. You can measure the Hall voltage with and without magnetic field at each current. A mount has been provided so that you can reposition the magnet accurately after each measurement. The true Hall voltage is the difference of these two measurements.

C. You can measure the Hall voltage with the magnetic field in opposite directions. (You can do this by flipping the sample instead of flipping the magnet.) The true Hall voltage should be the average of these two measurements.

Measure the magnetic field with a gaussmeter and **determine the carrier densities**. Measure V_R at room temperature for several currents (not exceeding $\pm 5mA$), determine the resistance between contacts (3,4) and then deduce the conductivity of each sample. Using the carrier densities from the second part of this experiment, **estimate the Hall mobilities** μ_h and μ_n.

Conductivity Versus Temperature

For a single constant current, immerse the samples in oil and determine the variation of the conductivity with temperature over the range -5°C (using dry ice) to 150°C (using the hot-plate).

– **Indicate the ranges of temperature over which the samples exhibit the characteristics of intrinsic and extrinsic conductivity.**

– **Is equation (4) consistent with the data over any temperature region?**

– **Determine the energy gap** using equation (4).

Bibliography

R. B. Adler *et al.*, Introduction to Semiconductor Physics, Wiley, 1964 (QC 612 S4A4).

C. Kittel, Introduction to Solid State Physics, Wiley, 6th Edition, 1986 (QC 171 K5).

An alternate experimental method to determine the energy gap is to measure the Hall voltage as a function of temperature. This has the advantage that the carrier densities are measured directly – and can be fit to equation (4) – independent of any assumptions about the temperature dependence of the mobilities. The experimental disadvantage is that a magnet makes it hard to use either a stirrer or a hot plate, so that the oil must be heated first and then carefully placed in the magnet. Data can only be taken as the oil cools, and thermal gradients are a concern. Ask the supervising professor about using a large electromagnet if you are interested in this method.