The Hall Effect

(update: August 2012)

List of appendices:

For additional information on the experiment see also:

http://www.ugrad.physics.mcgill.ca/wiki/index.php/Hall_Effect

The Hall Effect and Properties of Semiconductors

Updated in August 2012.

Warnings:

- Be careful not to exceed a sample temperature of 383K. To minimize the possibility of overheating, never leave the equipment unattended while the heater is on;

- Manipulate the liquid nitrogen carefully. In addition, be careful when the sample is at very low or very high temperatures;

- The sample and its wiring are very fragile - manipulate very carefully;

- Do not forget to turn off the various power supplies when leaving the experiment, except when taking measurements overnight.

- If your experiment uses an electromagnet, make sure that the cooling water is turned on when you use the magnet and turned off when you do not.

- The cold-junction compensator gets its internal power from a battery; make sure that it is switched ON when you use it (you will otherwise get an initial temperature around 0°C) and that that you turn it OFF when you do not use it.

Contents

1 Introduction

The Hall effect has played an important role in the investigation of conduction processes. In the present experiment, some basic properties of semiconductors will be illustrated by the means of measurements of the Hall coefficient R_H and of the resistivity ρ of a germanium crystal. The measurements of the temperature dependence of ρ and R_H can yield information on (or illustrate):

- the processes of intrinsic and extrinsic conduction in semiconductors;
- the conduction mechanism;
- the nature of the dopant;
- the bandgap between the valence and the conduction band of the semiconductor;
- the concentration of impurity carriers;
- the mobility of the carriers.

2 Theory

2.1 Conduction in Semiconductors

One of the most striking features of quantum mechanics is the quantization of the energy levels of individual atoms. When the atoms aggregate in a crystal lattice, however, the extremely high number of possible interactions makes it such that a near-continuum of energies are accessible to the electrons. However, emphasis should be put on the word "near", here, as there may still exist a forbidden energy region between electrons from the outermost shell in their ground state and electrons in the first excited state from the outermost shell - this gives rise to the existence of multiple **energy bands**. This is the case in insulators, for example; the effect is illustrated in figure (1)[1].
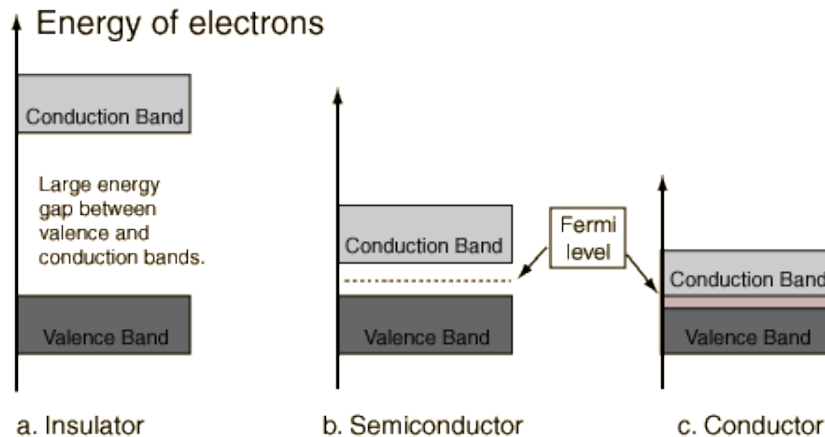

Figure 1: Illustration of the energy bands phenomenon for the usual three types of materials.

The wavefunction of an electron in the conduction band allows it to move from one atom to another in the crystal lattice; the wavefunction of electrons in the valence band makes them confined to a single atom, such that those electrons do not partake in the conduction process. In metals, the valence and the conduction bands overlap, such that conductive states are readily accessible; in insulators, the bands are separated by an energy called the **band-gap energy** - this is also the case for semiconductors, although the separation is small -, such that the vast majority of electrons will lie in the valence band.

However, even a very small separation between the bands reduces the conductivity such that the pure semiconductor is unusable in most applications. To bring the conductivity up to a more appropriate level, a process called **doping** is very commonly used; this consists of deliberately adding impurities to the semiconductor to

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[1]Taken from Georgia State University, Hyperphysics - Hall Effect, http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/hall.html

increase its conductivity. Dopants are said to provide a mode of conduction by **extrinsic carriers**, whereas the semiconductor electrons in the conduction band are said to be **intrinsic carriers**.

At low temperatures, very few semiconductor atoms are excited into the conduction band by thermal processes, such that the mode of conduction is mostly extrinsic; at high temperatures, the extrinsic processes drop out for reasons that will be explained later and intrinsic processes take over as thermal excitations bring a sufficient number of atoms to the conduction band.

2.2 Resistivity, Conductivity and Mobility in Semiconductors

A full derivation of the results used in this section may be found in Appendix A

The common electrical resistance R, for some sample of a given material of a length L and of cross-sectional area S, is defined by:

$$R = \frac{\rho L}{S} \tag{1}$$

where ρ is a temperature-dependent material property (unlike the resistance) called the **resistivity** of the material, with units of $\Omega \cdot m$. The inverse of this quantity, $\sigma = 1/\rho$, is called the **conductivity** of the material, which is also defined in electromagnetic theory as:

$$\mathbf{J} = \sigma \mathbf{E} \tag{2}$$

where $\mathbf{J}$ and $\mathbf{E}$ are the usual vectorial current density and electric field. If we only have negative charge carriers, the former may also be expressed as:

$$\mathbf{J} = en\mathbf{v} \tag{3}$$

where e is the charge of the electron, n is the negative carrier density in the sample and $\mathbf{v}$ is the mean velocity of the charge carriers.

For semiconductors as studied in this experiment, it may be shown that the mean velocity is approximately equal to:

$$\mathbf{v} \approx \frac{e\lambda \mathbf{E}}{2\sqrt{3kT \cdot m}} \tag{4}$$

where λ is the mean free path of the carriers (average distance before being scattered by an atom), k is the Boltzmann constant, T is the temperature of the sample and m is the effective carrier mass. It may further be shown that the mean free path λ goes as $1/kT$; all in all, if the number of carriers is constant, using the last three equations, we may expect that

$$\sigma \propto T^{-3/2} \rightarrow \rho \propto T^{3/2} \tag{5}$$

However, the condition that the number of carriers remains constant only holds when intrinsic conduction is approximately null; the number of carriers will increase if a substantial number of valence electrons reaches the conduction band. Thus, we may only use equation (5) if it appears evident that the conduction is almost all due to extrinsic processes.

At higher temperatures, the contribution of extrinsic processes to the conduction becomes more and more limited and we arrive in the intrinsic region. As the carrier density varies with temperature in this case, other means to find a relationship for the conductivity as a function of the temperature must be used. Here, the combined number of holes and electrons is constant; we may then expect, from statistical mechanics, that the carrier density, and thus the electrical conductivity, follows a Maxwell distribution:

$$\sigma \propto e^{E_g/2kT} \tag{6}$$

Where E_g is the band-gap energy.

In the scope of this experiment, the two regions are readily distinguishable - the conductivity first decreases with the temperature as we progress in the extrinsic region; then, as intrinsic contributions start to matter, the conductivity starts to increase as electrons are able to reach the conduction band. A simple measurement of the conductivity as a function of the temperature then provides valuable insight on both mechanisms of conduction and their functional relationship. By carefully neglecting the transitory region where both types of conduction are significant, we may also extract the band-gap energy by curve fitting over the intrinsic region.

A commonly used physical quantity to quantify these effects is called the **mobility** μ of the charge carriers, defined in electromagnetic theory by $\mathbf{v} = \mu \mathbf{E}$. Using the previous equations, it is easy to see that:

$$\mu = \frac{\sigma}{ne} \quad . \tag{7}$$

The mobility will come into play later.

2.3 Hall Effect

The directions x, y, z indicated by the subscripts in the equation correspond to those of the coordinate system defined on figure (2)[2].
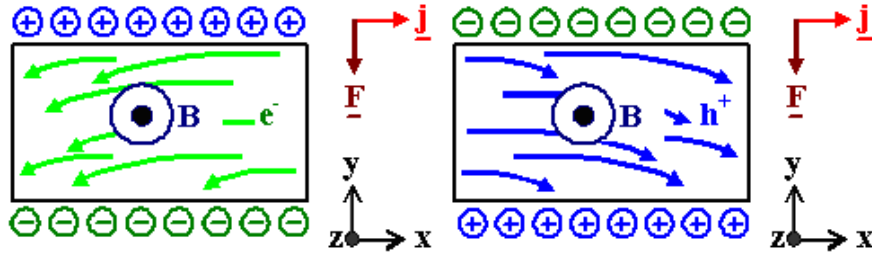

Figure 2: Illustration of the Hall effect on both positive and negative carriers. Note that the magnetic force is in the same direction in both cases.

What if we add a magnetic field to the sample while current is driven through it? The magnetic field will induce a force that will cause the carriers to pile-up on one side of the material; the pile-up will create a repulsive electric force in the opposite direction. At equilibrium, this makes it such that we have an asymmetric distribution of charges in the sample, which creates a potential difference between its sides. This effect, illustrated in figure (2), is known as the **Hall effect**, and the resulting potential difference is called the **Hall voltage** V_H. Another way to quantify this effect is by using the **Hall coefficient** R_H, defined as:

$$R_H = \frac{E_y}{J_x B} = \frac{V_H d}{IB} = \frac{1}{ne} \tag{8}$$

where E_y is the magnitude of the electric field created by the charge pile-up, J_x is the current density in the sample, B is the magnitude of the magnetic field, d is the thickness of the sample (for a rectangular, perpendicular to the field chip), n is the charge carrier density and e is the electronic charge.

Yet another way of quantifying the effect is to use the **Hall angle** ϕ_H:

$$\phi_H = \frac{V_y}{V_x} = \frac{E_y w}{E_x l} = \frac{w}{l} \mu_H B \tag{9}$$

where V_x, in this case, is the Hall voltage drop across a width w on the sample, V_y is the voltage drop across a length l on the sample, E_y and E_x are corresponding electric fields, and μ_H corresponds to the mobility introduced in the previous section.

Note, however, that in a semiconductor, the charge carriers may be both the conduction electrons (represented by the negative carrier density n) or the "holes" that they leave behind (acting as "positive" charges, and represented by the positive carrier density p). The charges are then pushed along the y-direction in different directions by the magnetic field; as no current may flow off the the sample, however, the net current must be zero, which yields the following condition:

$$v_{y+} p = v_{y-} n \tag{10}$$

where $v_{y\pm}$ denote the drift velocity of the positive or negative carriers in the y-direction. Using the definitions of the previous section, we can obtain:

$$v_{y\pm} = \mu_\pm (\mu_\pm E_x B \mp E_y) \tag{11}$$

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[2]Taken from H.Foell, *The Hall Effect*, University of Kiel, http://www.tf.uni-kiel.de/matwis/amat/mw2_ge/kap_2/backbone/r2_1_3.html

where $\mu_{\pm}$ represents the mobility associated to each carrier type. As we may express the conductivity of a semiconductor with both types of carriers as $\sigma = e(\mu_+ p + \mu_- n)$, we may use the last two equations into equation (8) to obtain:

$$R_H = \frac{\mu_+^2 p - \mu_-^2 n}{e(\mu_+ p - \mu_- n)} \tag{12}$$

Now, the mobilities vary with temperature, and very usually, $\mu_- > \mu_+$. Therefore, for a semiconductor where $p > n$, we expect R_H to change sign at some temperature (as p increases and n decreases with increasing temperature) - such semiconductors are said to be of the p-type and have holes as the majority carrier, by opposition to the n-type which has electrons as the majority carrier. A study of the Hall coefficient thus permits an easy determination of the type of semiconductor we are dealing with.

2.4 Magneto-Resistance Effect

In the presence of a magnetic field, the electrical resistance of some sample is seen to change - this is due to the non-uniform charge density changing the normal trajectory of the electrons, which are then observed to have a reduced mean path λ. A more detailed discussion of this effect is included in Appendix A. The change in resistivity $\Delta\rho = \rho - \rho_0$, where ρ_0 is the resistivity in the absence of a magnetic field, if small, may be related to the magnetic field by a power expansion as:

$$\Delta\rho \approx C \cdot B^2 \tag{13}$$

to first-order, where C is a constant. Note that as Ohm's law illustrates a proportionality between ρ and the voltage across the sample in this situation,

$$\Delta V \approx D \cdot B^2 \tag{14}$$

where D is a constant and ΔV is the voltage across the sample. The reasoning behind these approximations is given in Appendix D.

3 Apparatus

The block diagram for most of the experiment is shown in figure (3). The individual components will be discussed below.
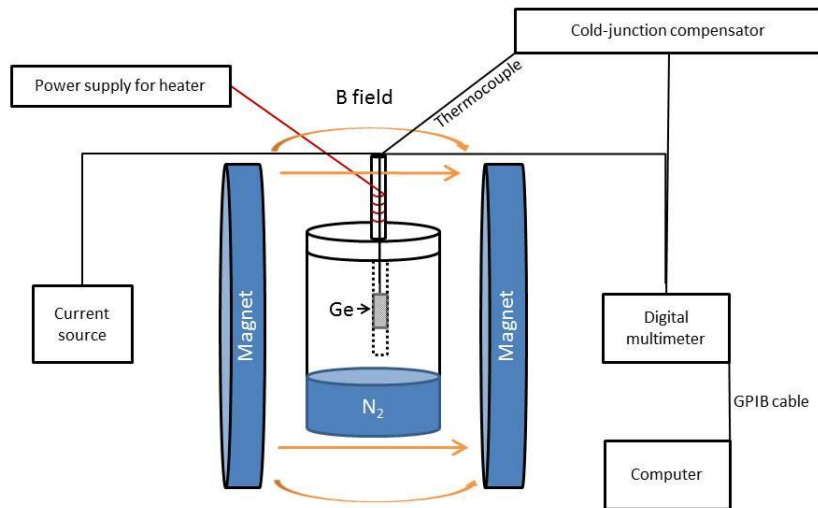

Figure 3: Block diagram for the experiment. Taken from a previous lab report.

Sample and Sample Holder

The germanium crystal is mounted on a sample holder. The crystal itself, the wiring and the sample holder are **very fragile**! The sample holder can be immersed into liquid nitrogen for studying the temperature dependence of the resistivity of the germanium crystal - this will be the first part of the experiment. A similar measurement with the crystal placed in the magnetic field will allow you to measure the Hall voltage as a function of the temperature in the second part of the experiment. In the final part of the experiment, you will measure the magneto-resistance of the crystal by measuring the resistivity of the germanium sample as a function of the strength of the magnetic field. As you can see, you will need your sample for the whole experiment - take good care of it! The voltages from the crystal are read using some thin and fragile wires. The connections are very easy to break and very difficult to reconnect. A schematic of the sample is shown in figure (4).
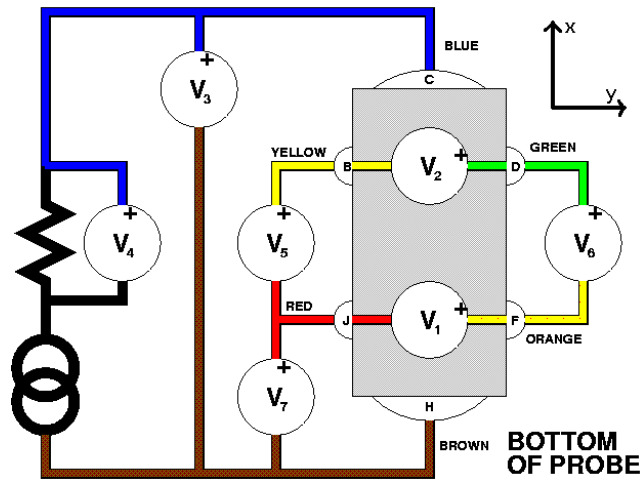

Figure 4: Schematic of the semiconductor chip showing the various voltages to be measured.

At its top end, the sample has a head with a connector. Here, you have to connect the gray cable to the green plastic connectors at the rear of the Keithley DMM; you will also have to connect the thermocouple wire to the cold-junction compensator using the separate wire coming out of the head of the sample holder. Also connect the heating DC power supply to the wires that are used for heating the sample.

The sample is of an approximately rectangular shape in our case, which enables us to easily obtain its resistivity from a measured voltage drop, using Ohm's law:

$$\rho = \frac{VA}{Il} \tag{15}$$

where V is the measured voltage drop, A is the cross-sectional area of the crystal, I is the current put through it and l is the length between the measuring points.

Constant Current Power Supply

This power supply provides a constant current through the germanium crystal - for the purposes of this experiment, a current of 1mA is sufficient. This instrument has to be connected through its rear to a copper-silver wire duo. Attach the copper wire to the positive output and the silver wire to the negative output of the power supply (this might already be done for you). You may choose the polarity of the current by using the **Output** button and setting it in either the **Revrs** or the **Norm** position. You may verify the accuracy of the current value by using another multimeter.

Variable DC Power Supply

At certain stages of the experiment, you will have to heat the sample. A variable DC power supply provides the power to the heater, which is attached to the sample. Locate the wires, which are attached to the heater

and then plug them into the output (red and black plugs) of the instrument. When heating the sample, make sure that you do not exceed a temperature higher than 383K! The thermal coupling between the heater and the sample is rather poor resulting in a long time constant for the heat to reach the sample; begin heating slowly and let some time pass before increasing heating.

Thermocouple System (With Cold-Junction Compensator)

The thermocouple system is used to measure the temperature of the crystal. The general working principles of thermocouples are described in Appendix B. A thermocouple in its most rudimentary form consists of two wires of a different material held together at one end. When heating the junction between the two wires, a potential difference between the open ends of the circuit is created, which may be related to the temperature difference between the junction and the open ends. In our experiment, the thermocouple actually measures the temperature of the copper block onto which the sample is mounted rather than the temperature of the sample itself. The sample is insulated from this copper block by a thin piece of insulating material. If the heating/cooling rates of the sample are slow enough, we may assume that the crystal and the copper block are at the same temperature.

A cold-junction compensator is then added to the thermocouple system; it provides a reference temperature to the thermocouple, which may otherwise only measure temperature differences. Make sure that the output of the cold-junction compensator is connected to the plastic connectors at the rear of the DMM by means of the cable with the white connector. Its input must be connected to the sample using the cable attached to the latter's top (blue connector). Since the compensator gets its internal power from a battery, make sure that it is switched ON when you use it (you will otherwise get an initial temperature around 0°C). Also, make sure that you turn it OFF when you do not use it.

Magnet

If your experiment uses an electromagnet, make sure that the cooling water is turned on when you use the magnet and turned off when you do not. You will be able to control the strength of the magnetic field by varying the current through the magnet, which is done by the means of another variable DC power supply (not pictured on figure (3)).

The magnetic field generated by the magnet is related to the current in the coil and not the voltage drop across the coil (think of the magnetic field generated by a solenoid). Thus, you should control the magnetic field by adjusting the current generated by the power supply. The power supply can work either by limiting the current or the voltage. Use the limiting current option. To use it in this option you first adjust the current to zero and then raise the limiting voltage to a higher value than needed. If then you increase the current control the voltage will adjust itself so as to provide the set current. Then if the resistance of the coil changes (e.g. because of a change of temperature) then voltage will adjust itself to maintain the set current.

The two-coil configuration of the magnet produces a magnetic field of near-constant magnitude and direction between the coils, and a nearly zero magnetic field outside of them.

Magnetic Field Measurement

You will have to measure the magnetic field between the poles of the electromagnet at various points in the experiment. This is done by using a dedicated Hall probe (see Appendix B for information on this device). Four wires are coming out of the probe. Two are connected to a power supply giving a specified current across the probe, normally to be set at 200mA, while the other two wires should be connected to a voltmeter. The latter gives the Hall voltage across the probe that can be related to the value of the magnetic field. Each probe has a different calibration relating the measured voltage to the value of the magnetic field. You should get the calibration equation applying to your probe from the technician in charge of the laboratory.

If needed, the laboratory has also an integrated Gaussmeter from LakeShore. If you need to use this instrument, you should get instruction from the instructors or from one of the lab technicians. You should be very careful while using that apparatus since its probe is very fragile and expensive.

Keithley Digital Multimeter (DMM)

The voltage readings from the sample, the current driven through the crystal and the temperature of the sample are all read into the DMM, which takes the measurements at a predefined time interval and transfers them to the computer. All connections may be seen at the back of the interface. Make sure that the `INPUT` button is pressed in so that data is read from the back of the interface.

As the DMM allows to read the eight different voltages from the crystal and the thermocouple, it acts as a multichannel device, then transferring the information to the computer via a PC-GPIB card. The voltages should appear in succession once the data acquisition software is running (more on that later). At the right end of the DMM's display, a number should indicate which voltage is being read (1 representing V_1, 2 representing V_2 and so forth).

If you want to use to the DMM without the computer (this may be useful for the last part of the experiment), you may, while the data acquisition software is turned off, simply press the `SCANNER` button on the front panel, then press the key corresponding to the given channel number associated to the voltage you want to study.

Software

A more complete discussion of the software is given in Appendix C. The appendix also discusses plotting and fitting software not included in this section.

The computer will be the final stage of data acquisition, storing the voltages, times and temperatures in text files, and will be the centre of data analysis. The experiment runs on Linux boxes, on which multiple home-made data analysis programs are included.

The reading of the various potential differences and of the temperature of the sample is done by the means of the `hall` software, which stores all of the relevant quantities in a ten-column text file (eight voltage drops, the temperature of the sample and the time), taking a measurement at a given rate which is adjustable with the DMM. To use the program, open a terminal and simply type `hall filename`, where `filename` is to be replaced with whatever you want the name of the output file to be. A graphical interface that looks a lot like the schematic of the sample in figure (4) will appear on the screen, with boxes showing numerical values for each voltage and with a supplemental box showing the temperature.

After the data acquisition is done, you will want to plot the data; `hall_process` will separate the initial ten-columns into eight separate files; the first seven (named `filename.1, filename.2...` bins V_1, V_2, ..., as a function of the sample temperature in a four-column format (mean bin temperature, mean bin voltage drop, statistical uncertainty, number of measurements in bin), while the last one returns temperature as a function of time (in seconds) in a two-column format (time, temperature). The syntax to be used in the terminal is `hall_process -b [binwidth] filename`, where `[binwidth]` is to be replaced by the wanted bin width in Kelvin, the default being 1K. You may then use your favorite plotting program to obtain the wanted graphs.

In the very likely event that you need to add, subtract, multiply or divide two datasets in two-column format, you may use the programs `hall_add`, `hall_subtract`, `hall_product` and `hall_quotient`, respectively, with the syntax `program -o outputfile file1 file2`, where `outputfile` is the name you want to give to the output file, `file1` and `file2` are the two input files to combine and `program` is the name of the program to be used.

You can also use a text editor to combine the data files; for example, you may want to combine measurements from liquid nitrogen temperature to room temperature with data from room temperature and above that may have been taken at a different time. You may also use it to delete sections of the data files that are irrelevant, such as long measurements at room temperature.

4   Experiment

4.1   Measurement of the Sample's Relevant Dimensions

As evidenced by equations (9) and (15), the dimensions of the semi-conductor used as the sample are necessary in order to perform a sound quantitative analysis. Your first task is thus to obtain those dimensions by using a travelling microscope. The microscope is located on a table just to the left when entering the lab. You may disassemble your sample by removing the top part from the aluminium cylinder, disconnecting the thermocouple and the gray wire connecting the sample to the DMM and unscrewing the copper tube, so that the germanium

chip becomes visible. The travelling microscope is straightforward enough to use; turn the lens to adjust the focus and use the lower right knob to displace the microscope. You may then use the soldering of the wires as a guide to measure the distance between the connections.

The wiring shown on figure (4) should be evident; you may then measure the distances corresponding to V_1 and V_2 (which may both be used as w in the formulas, provided that the corresponding voltage is used - you may also take the average) as well as the distances corresponding to V_5 and V_6 (which may both be used as l in the formulas, again, provided that the corresponding voltage is used) and the thickness of the chip (corresponding to t in the formulas). You may then easily derive the cross-section A.

4.2   Measurement of the Resistivity of Germanium as a Function of Temperature

Once the dimensions are obtained, you may study the resistivity of the germanium crystal as a function of its temperature. In order to do so, you need to measure the voltage along the crystal as a constant current of 1mA is applied to it for various sample temperatures - in our case, you will have it warming up from a temperature close to 150K to a final temperature around 383K. **Do not exceed this maximum temperature**, as the solder used to attach the wires to the sample may start to melt.

You may leave the sample between the coils of the magnet - however, for this part of the experiment, no field is to be applied. You will first need to cool down the sample to around 150K by putting liquid nitrogen into the sample's Thermos flask - use the provided bottle and the gloves to protect yourself. Once you get down to this temperature and that it stays relatively stable, you may start to take data as the sample heats back up to about room temperature without applied heating. Once you reach the neighborhood of 295K, you may start heating the sample with the DC power supply. You may use a voltage up to 28V, but remember that the temperature reading will only be accurate if we have thermal equilibrium between the germanium sample and the copper block enclosing it. It is thus wise to use a lower initial voltage - perhaps between 5V and 10V - so that the heating is slower, and to increase the voltage when needed. A heating rate of about 1K per minute is desirable.

As mentioned, the `hall` program is used to collect the data. After starting the program, non-zero numerical values should start to fill up the boxes of the graphical interface, and "HALL EFFECT 2005" should be read immediately on the DMM's display - check your connections if either of those things does not occur. When doing the initial fast cooling, you may start a dummy data acquisition to monitor the temperature of the sample with the graphical interface, then start a new one when the sample is heated back up.

A plot of the resistivity against the temperature should return a curve with a definite peak below which the mode of conduction is mostly extrinsic and above which it is mostly intrinsic; you may fit the former to a power law (of form $\rho(T) = a \cdot T^b$, where a and b are fit parameters) to verify the $\rho \propto T^{3/2}$ dependence, and fit the latter part to an exponential (of form $\rho = a \cdot e^{b/T}$, where a and b are fit parameters) to obtain the band-gap energy from equation (6). You may also compare the resistivity of your chip with the manufacturer's value (given in Appendix E) and note the temperature of peak resistivity.

4.3   Measurement of the Hall Coefficient as a Function of Temperature

In this part of the experiment, you will measure the Hall voltage at different temperatures. Using this data, you will be able to compute the Hall coefficient for germanium using the data analysis programs. This obviously involves the introduction of a constant magnetic field from the coils between which you put the sample - you may put on a current with the magnet's DC power supply so that the field measured with the Hall probe or the Gaussmeter is near 0.5T. You may then promptly play around with the sample position and the field magnitude so to observe the effects on the various voltage drops. Make sure that the sample is placed in the maximal region of the field.

Particularly, you will have to find the orientation of the sample that maximizes the voltage drops - this happens when the crystal is perpendicular to the magnetic field. To find it, simply rotate the sample and note the voltage drops V_1 and V_2 at various angles. To eliminate possible offset voltages between the contacts on both sides of the crystal, it is recommended that you take two sets of measurements - one at the orientation that maximizes the voltage, and one with the sample turned by an angle of 180°, and then subtract the two measurements (and divide by two to get an average). Those should in theory yield the same results, but it is experimental work that we are doing, here. The temperature variation is done in similar fashion to the resistivity measurements.

Here, you have a lot left to analyse. Other than the obvious analysis of the Hall voltage as a function of the temperature, which you may relate to the extrinsic and intrinsic regimes, you may analyse plots of the Hall mobility, the Hall coefficient and the Hall angle as a function of the temperature. From the Hall mobility plot, you may check if the proportionality to $T^{-3/2}$ in the extrinsic regime also applies for the Hall mobility. With the Hall coefficient plot, you may compare your result to the manufacturer's value (given in Appendix E) as well as extracting the approximate density n of impurities from the coefficient at room temperature using equation (8) - indeed, at room temperature, extrinsic carriers are saturated in the conduction band and intrinsic effects are minimal. You may also determine if the studied semiconductor is of the p or the n type from that same plot, as mentioned earlier.

4.4 Measurement of the Magneto-Resistance as a Function of the Magnetic Field Intensity

You will also study how the intensity of the magnetic field affects the resistance of the germanium sample. To do so, both the sample and the gaussmeter will need to be encased in the magnetic field, one next to another; you may hold them in place with the provided retorque stand. Place the sample so that the Hall voltage is maximal, as in the previous section. An interesting expansion to the experiment might be to study this effect as a function of the angle of the sample, and thus as a function of the orientation of the lattice relatively to the magnetic field - a discussion is included in Appendix D.

In this part of the experiment, fields ranging from about 0.05T to about 0.50T are appropriate. There is no need for the computer or for a temperature variation in this case - you may read the two voltages of interest, namely V_5 and V_6, directly from the DMM.

A fit to a power law is still in order here; you expect a quadratic dependence as per equation (13).

5 Goals

In short, you must:

- Measure the resistivity of germanium as a function of temperature and deduce conclusions regarding the conduction mechanism;

- Measure the dependence of the Hall voltage across the sample on temperature;

- Measure the magneto-resistance of the sample as a function of the magnetic field intensity;

- (optional) Be creative! You may for instance study the dependence of the magneto-resistance effect on the orientation of the sample, study the heating rate of the sample, or do whatever else that may come to mind.

Good luck!