Resistivity and Hall effect in *p* and *n* Germanium.

Objective

Measure the Hall coefficient, R_H, and electrical conductivity, σ, of *n* and *p* type Germanium to determine the electron (hole) carrier concentration, $n_{n(p)}$, and mobility, μ. In addition, determine the band gap in pure Germanium by measuring the conductivity.

Background and Theory

Read the following references prior to the lab. Copies of these references are provided on LEARN. An introductory condensed matter physics course is a valuable primer for this experiment.

References:

1. Leybold Physics Leaflets P7.2.1.1, P7.2.1.4 and P7.2.1.5 (LD Didactic GmbH).

2. Adir Bar-Lev, Semiconductors and Electronic Devices, 2nd edition, Prentice-Hall, 1984

3. Bolyestad and Nashelsky, Electronic Devices and Circuit Theory, Canadian edition, Prentice-Hall, 1999.

4. C. Kittel, Introduction to Solid State Physics.

Procedure

The Samples:

In this experiment you will investigate 3 samples of Ge; undoped, *n* doped and *p* doped. The samples are prewired on a circuit board that contains the sample's voltage and current connections, a sample heater and resistance thermometer.   The samples are to be inserted into DIN socket on the Hall effect base unit, which allows the sample to be wired for measurement. The dimensions of all samples are $w = 20$ mm (length), $b = 10$ mm (height), $d = 1$ mm (thickness).

Temperature measurement: Each module uses a Pt100 resistance thermometer to measure the temperature. These thermometers are platinum resistors that have a calibrated resistance vs. temperature (the name Pt100 indicates R = 100 Ω at 0 $^{\text{o}}$C). The plug-in board includes an amplifier that outputs a voltage that is proportional to the temperature and is given by

$$T = \left(100 \ \frac{K}{V}\right) U_A + 273.15K \quad (1)$$

where T is the temperature in K and U_A is the thermometer voltage.

Part 1: Measure the conductivity in undoped Ge to determine the band gap.

1. Mount the undoped Ge sample (586-851) into the Hall effect measurement base unit (586-850).
2. Connect the 2 Agilent 34401A multimeter and the Pasco SF9584 PS power supply to the base unit to power the heater and measure the thermometer voltage and sample resistance (see figure 1).
3. Set the voltage on the power supply to 15V. Power must be supplied to the heater in order to measure the thermometer temperature.
4. Set the data acquisition software to monitor resistance. Start the data acquisition software.
5. Once the software is logging the data and the data is being displayed properly, press the black "Heater" button on the Hall effect base unit. The red light will turn on and the sample will begin to rapidly heat up. The heater will automatically turn off around 440 K in order to protect the unit from overheating. Measure the resistance both heating and cooling. (The measurement is more reliable during cooling and should be used for your analysis. Comment in your report on why this might be.)
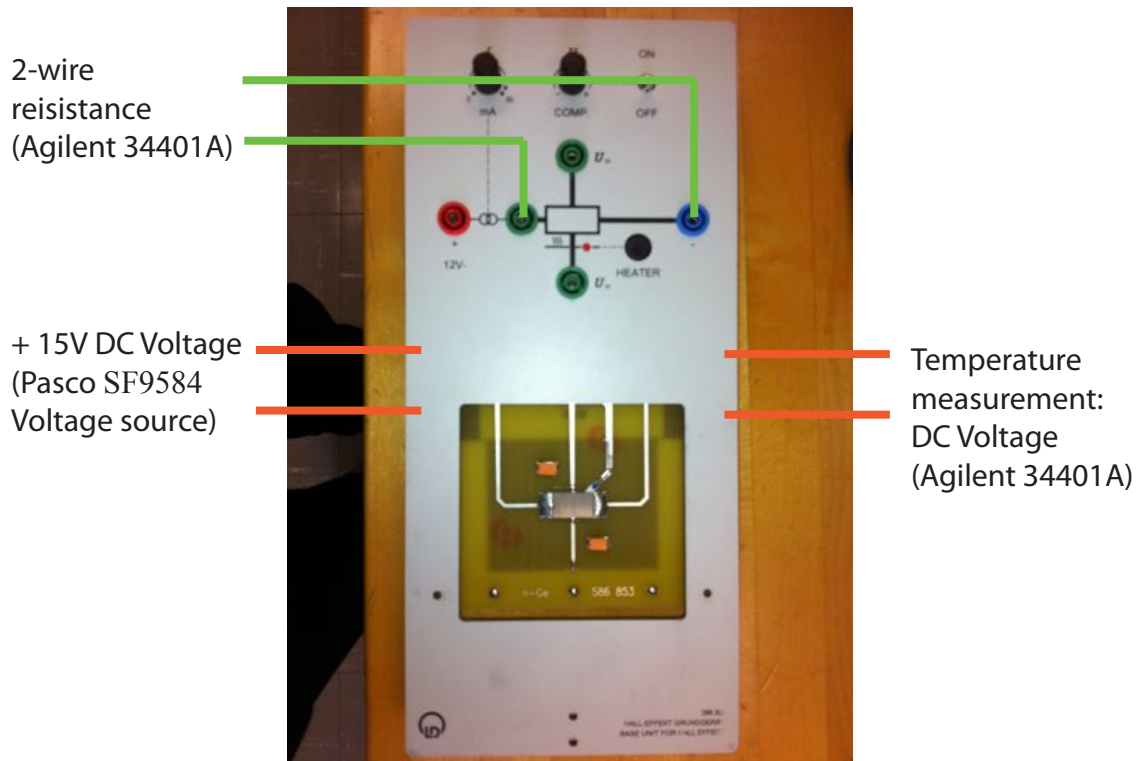
2-wire
reisistance
(Agilent 34401A)

+ 15V DC Voltage
(Pasco SF9584
Voltage source)

Temperature
measurement:
DC Voltage
(Agilent 34401A)

Figure 1: Wiring diagram for resistance vs. temperature measurement.

Part 2: Hall effect and conductivity at room temperature:

1. Choose either the *p*-type or *n*-type sample and connect it to the electronics as shown in figure 2 to measure the longitudinal voltage *U*. Ensure that a 10kΩ current limiting resistor is connected in series with the sample. This will protect the sample from excessive current damaging the sample.
2. Increase the voltage across the sample to achieve a sample current ~ 1 mA. Measure the longitudinal voltage, *U*.
3. Keeping the sample current constant, rewire the sample holder to measure the transverse voltage, U_H.
4. Mount the sample in the magnet gap. Make sure the plane of the sample-mounting card is perpendicular to the direction of the magnetic field. Tightly secure the holder rod into place using the clamp. *Make note of the exact orientation of the sample contacts with respect to the magnetic field direction.*
5. Turn on the magnet power supply (ensure that the magnet power supply current is set to zero before turning on). Measure U_H as a function of magnet current, I_m, for I_m from 0 to 20 A in 2.5 A steps. The magnetic field strength *B* is related to the magnet current by

$$B = (0.0457 \text{ T/A})I_m + 0.0104 \text{ T}. \qquad (2)$$

6. Using a loop of wire connected to the HP 3441A multimeter, determine the actual direction of the magnetic field. This can be done multiple ways. Consider using Lenz's law, which states that the induced EMF caused by a change in magnetic flux through a loop of wire induces a current that opposes the change in the magnetic flux:

$$EMF \propto -N\frac{d\Phi}{dt}, \qquad (3)$$

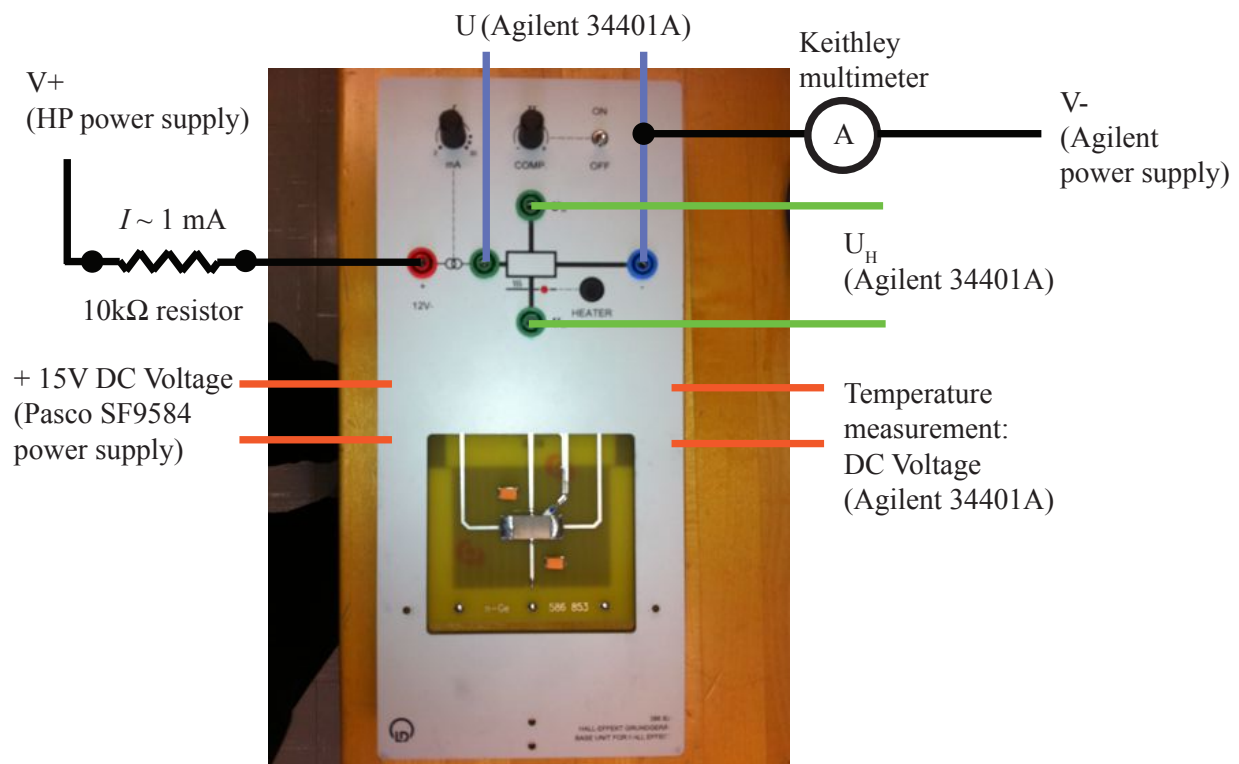where Φ is the flux and N is the number of turns of the coil.

Figure 2: Wiring diagram for Hall voltage measurement

Part 3: Hall voltage vs temperature:
1. Set the magnet current to 15A.
2. Set the data acquisition software to monitor voltage. Start the data acquisition software and measure the hall voltage both heating and cooling. (As before, the measurement is more reliable during cooling and should be used for your analysis)
3. Repeat parts 2 and 3 for the remaining sample.

Analysis:

1. Determine the band-gap of Ge from the temperature dependence of the resistance of the undoped Ge sample. (Use a plot of $\ln(R)$ vs $1/T$).

2. Determine the Hall co-efficient, R_H, and the carrier density of the n and p doped Ge samples from your plots of Hall voltage, V_H, vs. magnetic field strength.

3. Evaluate the room temperature resistivity for each sample, and using this information, evaluate the room temperature carrier mobility, μ, of the n and p doped Ge samples.

4. Following the Leybold physics leaflet P7.2.1.4, it can be shown that the temperature dependence of the Hall co-efficient can be used demonstrate the cross-over from a regime where the Hall co-efficient is dominated by impurity induced carriers to a regime where intrinsic carriers generated by thermal excitation across the band-gap play a significant role in the Hall co-efficient. Moreover, you can model the temperature dependence of the Hall co-efficient to extract values for $k = \mu_n/\mu_p$, the ratio of the electron to hole motilities and N_0, the effective density of states.

   Specifically, you can fit the temperature dependence of the Hall coefficient for the p-doped sample to

   $$R_H(T) = \frac{1}{e} \frac{p_S + \left(\sqrt{\frac{p_S^2}{4} + N_0^2 e^{-E_g/k_B T}} - \frac{p_S}{2} \right)(1-k^2)}{\left(p_S + \left(\sqrt{\frac{p_S^2}{4} + N_0^2 e^{-E_g/k_B T}} - \frac{p_S}{2} \right)(1+k) \right)^2}, \quad (4)$$

   using the values of E_g and p_S that you have already determined. Note, the derivation of (4) follows from

   $$R_H = \frac{1}{e} \frac{p - nk^2}{(p+nk)^2}, \quad (5)$$

   $$p = p_E + p_S, \quad (6)$$

   and

   $$n = n_E = p_E, \quad (7)$$

   where S and E denote the impurity doped and intrinsic carriers respectively. Substituting (6) and (7) into (5) gives,

$$R_H(T) = \frac{1}{e} \frac{p_S + p_E\left(1 - k^2\right)}{\left(p_S + p_E\left(1 + k\right)\right)^2} . \quad (8)$$

As shown in the Leybold physics leaflet P7.2.1.4, p_E can be expressed as

$$p_E = -\frac{p_S}{2} + \sqrt{\frac{p_S^2}{4} + \eta^2} , \quad (9)$$

where

$$\eta^2 \approx N_0^2 e^{-E_g/k_B T} . \quad (10)$$

As such, substituting (9) and (10) into (8) gives (4).

Although the above set of equations are worked out for the case of p-doped Ge, an analogous expression can be obtained for n-doped Ge:

$$R_H(T) = \frac{-1}{e} \frac{n_S + \left(\sqrt{\frac{n_S^2}{4} + N_0^2 e^{-E_g/k_B T}} - \frac{n_S}{2}\right)\left(1 - \frac{1}{k^2}\right)}{\left(n_S + \left(\sqrt{\frac{n_S^2}{4} + N_0^2 e^{-E_g/k_B T}} - \frac{n_S}{2}\right)\left(1 + \frac{1}{k}\right)\right)^2}$$

$$(11)$$

Fit the data for both the n-Ge and p-Ge samples to determine values of k and N_0.