The Hall Effect in Germanium

Abstract

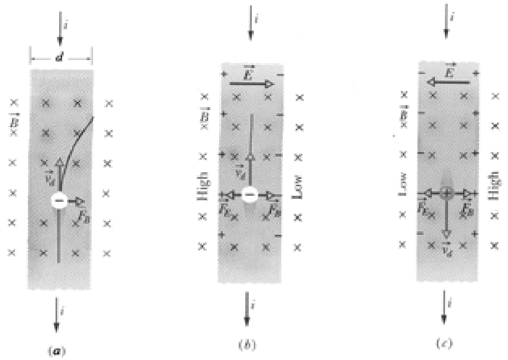
1. I determined the band gap of an undoped sample of germanium.
2. I Measuring the Hall voltage of both n-type and p-type germanium. Calculated the hall coefficient R_H, the carrier mobility μ_H and the carrier concentration, *n*.

Theory

The Hall Effect

A beam of electrons can be deflected by a magnetic field. Metals are full of free electrons that freely roam around the stationary protons. Edwin H. Hall found that these drifting conduction electrons can also be deflected when a magnetic field is applied. The diagram below taken from "The Fundamentals of Physics" by Halliway, Resnick and Walker, shows the Hall Effect on a strip of metal. A piece of metal, in our case Germanium as a current applied to it, (indicated as *i* below.) which run from the top to the bottom. Electrons (the charge carriers) drift in the opposite direction to the current at a drift speed of V_d.

A magnetic field, $\vec{B}$ is applied and to the strip and the drifting electrons are deflected by the magnetic deflecting force, F_B. This is shown below in the diagram labelled (a) where the black line represents the path of the drifting electrons which move to the right of the Ge strip.



(a) (b) (c)

“As time goes on, electron move to the right, mostly piling up on to the right edge of the strip, leaving uncompensated positive charges in fixed positions at the left edge”(1). An electric field $\vec{E}$ is produce by the separation of the negative and positive charge within the strip, shown above in the diagram labelled (b). The electrons deflected to the right by the magnetic force, F_B are now being deflected to the left by an electric force F_E. “An equilibrium quickly develops in the which the electric force on each electron builds up until it just cancels out the magnetic force”(1). The diagram labelled (b) above shows that F_B and F_E are balanced and the drifting electrons drift in a straight line from bottom to top a drift speed of V_d. no more electrons build up on the right so the $\vec{E}$ does not increase anymore.

“The *Hall potential difference* V is associated with the electric field across the strip width d”(1)

The potential difference is given by

$$V = Ed$$

If a voltmeter is connected across the width of the strip, the potential difference can be measured. The voltmeter can also indicate which side of the strip has a higher potential and with this information we can find out whether the charge carriers are positive or negative. We can find this out because if the charge carrier was positive (shown above in the diagram labelled (c)) moving from top to bottom, they would also be pushed to the right by the F_B and the right edge of the strip (instead of the left edge with negatively charged carriers) would have a higher potential.

“The conductivity, σ_o, carrier mobility, μ_H, and the carrier concentration, n are all connected by a factor called the Hall coefficient, R_H”(3).

$$R_H = \frac{U_H}{B}\frac{d}{I}$$

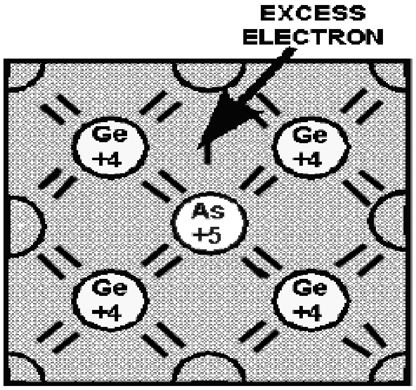
$$\mu_H = R_H \sigma_0$$

$$n = \frac{1}{eR_H}$$

Crystal Doping

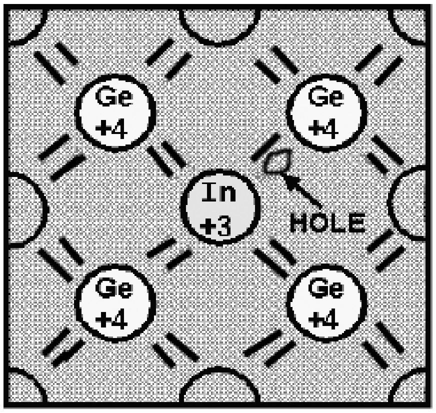
“Crystal doping is an efficient method of increasing current flow in semiconductors is by adding very small amounts of selected additives to them, generally no more than a few parts per million” (2). Doping therefore increase the amount of free charges that can flow.

“The N-type impurity loses its extra valence electron easily when added to a semiconductor material, and in so doing, increases the conductivity of the material by contributing a free electron. This type of impurity has 5 valence electrons and is called a PENTAVALENT impurity. Arsenic, antimony, bismuth, and phosphorous are pentavalent impurities. Because these materials give or donate one electron to the doped material, they are also called DONOR impurities”(2)
Below in a diagram of Germanium crystal doped with arsenic,(taken from reference (2)).



“The p-type impurity, when added to a semiconductor material, tends to compensate for its deficiency of 1 valence electron by acquiring an electron from its neighbour. Impurities of this type have only 3 valence electrons and are called TRIVALENT impurities. Aluminium, indium, gallium, and boron are trivalent impurities. Because these materials accept 1 electron from the doped material, they are also called ACCEPTOR impurities”, (2).

Below in a diagram of Germanium crystal doped with indium, (taken from reference (2)).



Band-gap/ energy gap

Band gaps are energy gaps that separated energy bands form the individual energy levels of crystalline solids. An energy gaps represents a range of energies that an electron cannot possess. The higher the energy of the band, the wider the energy gap. The energy gap can be determined from the from the equation

$$b = \frac{E_g}{2k}$$

Where E_g= the Energy Gap, k = Boltzmann's constant, T = absolute temperature and b can be determined from the straight line graph of In(σ) against 1/T of the solid (In our case undoped Ge)

Part 1: Determining the band-gap of an undoped sample of germanium.

I measured the current and the voltage across the undoped germanium, Ge sample as a function of temperature. From these measurements I calculated the conductivity, σ and plotted it against the reciprocal of the temperature, T. I obtained a linear plot and determined the energy gap of undoped germanium from the slope of this plot.

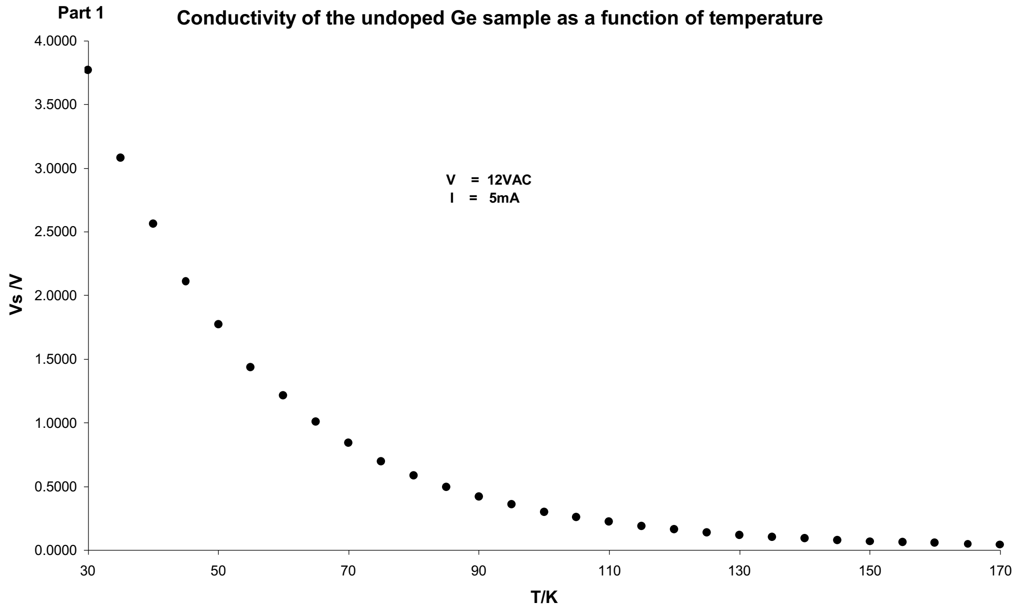
Set-up and procedure

The experimental set-up for part 1 is shown in Appendix B, Fig.1.

Measuring the sample voltage, V_s as a function of temperature, T

- The undoped Ge was put into guild-groove of the Hall effects module.
- The power unit was set at 12VAC which is connected to the Hall effects module.
- A voltmeter was used to measure the voltage across the sample, V_s.
- The temperature was read off of the Hall effects module.
- The current was set to 5mA and was kept constant during the measurements, but the voltage changed with the change in temperature.
- The sample was heated up by turning on the heating coil in the Hall effects module.
- When the sample reached 170ºC the coil was switched off and the voltage was measured every 10ºC until the temperature reached room temperature.
- See Appendix B, table of results part 1 for the voltage and temperature measurements.

- The graph (below) of sample voltage, V_s as a function of the temperature, T was obtained.



Calculating the conductivity, σ

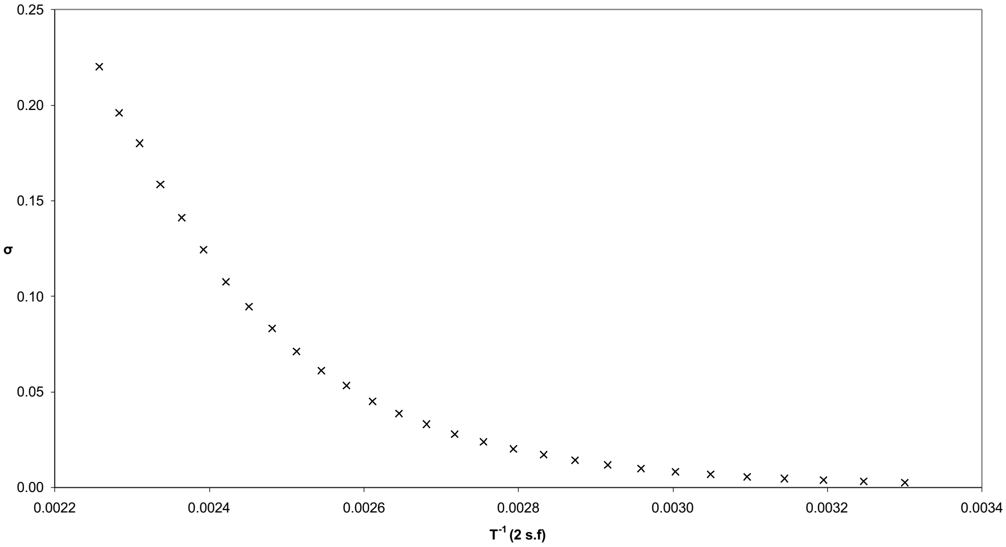
- Used the following equation to calculate the conductivity, σ

$$\sigma = \frac{1}{\rho} = \frac{l}{A}\frac{I}{U}$$

Where ρ = specific resisitivity, l = length of the sample, A = cross section are of sample, I = current, U = voltage. the dimensions of the Undoped Ge sample is 20x10x1mm.

- See Appendix B, table of results part 1 for the conductivity calculated.
- The graph (below) of conductivity, σ as a function of the inverse temperature, T^{-1} was obtained.

Conductivity of a semi-conductor as a function of the reciprical of the temperature

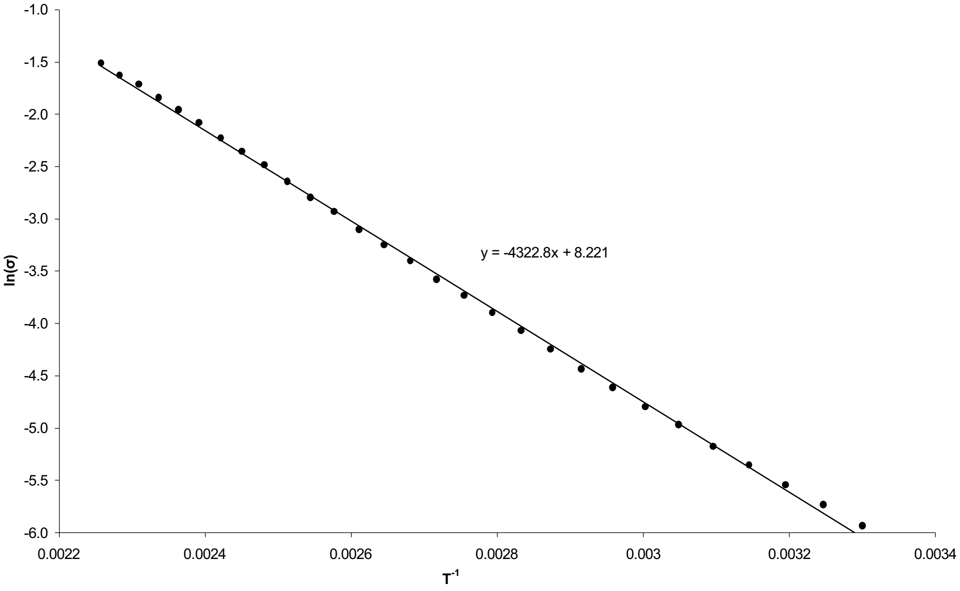


Determining the energy gap, E_g

- I calculated In(σ) and plotted it against T^{-1}
- I obtained a straight line graph (shown below) of which the gradient equals b.

Where, $b = -\frac{E_g}{2k}$, k = boltzmann's constant

Graph of in(σ) as a fuction of T^{-1}



- From the graph shown above, the gradient, b = 43228.
- Therefore E_g= 0.74eVs, Where b = 43288 and k = 8.6 x $10^{-5}eVk^{-1}$.

Part 2: Hall Effect measurements of n-type and p-type germanium.

1. I took four measurements on both the p-type and the n-type germanium.
2. Measured the Hall Voltage,U_H as function of current at room temperature and with a uniform magnetic field.
3. Measured the voltage across the sample as a function of magnetic flux density, B, at room temperature and with a constant control current.
4. Measured the Hall Voltage,U_H as a function of the magnetic flux density, B, at room temperature. From these readings I determined the Hall coefficient, R_H, and the sign of the charge carriers. I also calculated the hall mobility, m_H, and the carrier density, n.
5. Measured the Hall Voltage, U_H, as a function of the temperature at uniform magnetic flux density, B.

Set-up and procedure

The experimental set-up for part 2 is shown in Appendix C, Fig.1.

The table of result for this section can be found in Appendix C.

- I performed all the measurements above on the p-type Ge first and then performed them on the n-type Ge.
- Place the doped Ge into the guide-groove of the Hall Effect Module.
- Connected the Hall effect Module to the Power Unit with was set to 12VAC
- The sample is place between the magnet

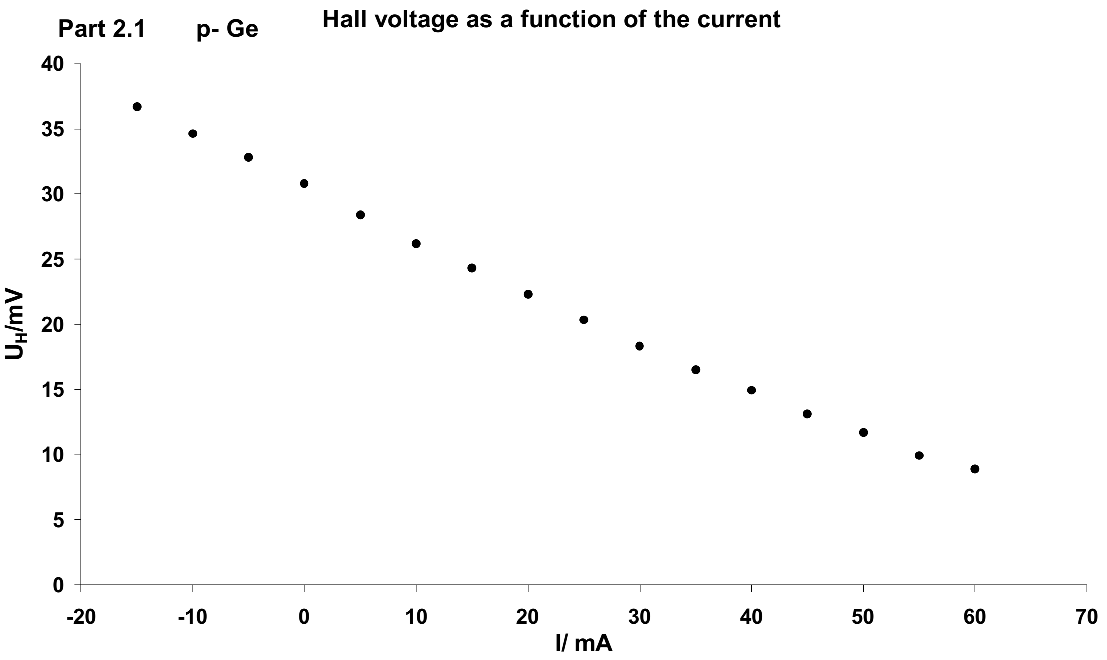
- The flux density was measured by a telsameter using a hall probe, which is place directly into the groove of the module.

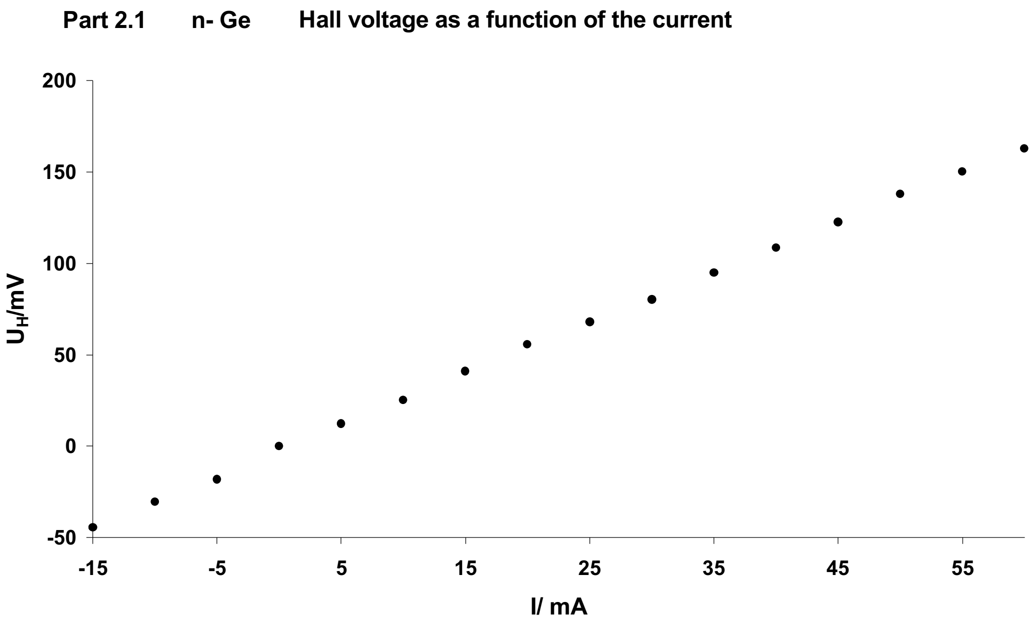
Measurements 1: Hall Voltage, U_H as a function of current, I

- Magnetic field was set to 250mT by changing the voltage and the current on the power supply.
- Multimeter was connected to the sockets of the Hall Voltage (U_H) on the Module
- Measured the Hall voltage with the multimeter, as a function of the current from 15mA up to 60mA in steps of ~5mA.
- The graph (below) of Hall Voltage, U_H as a function of current, I was obtained for p-type Ge and n-type Ge.
- These straight line graphs show a linear relationship between the current *I* and the Hall voltage U_H

$$U_H = \alpha I$$

Where α = constant of proportionality.



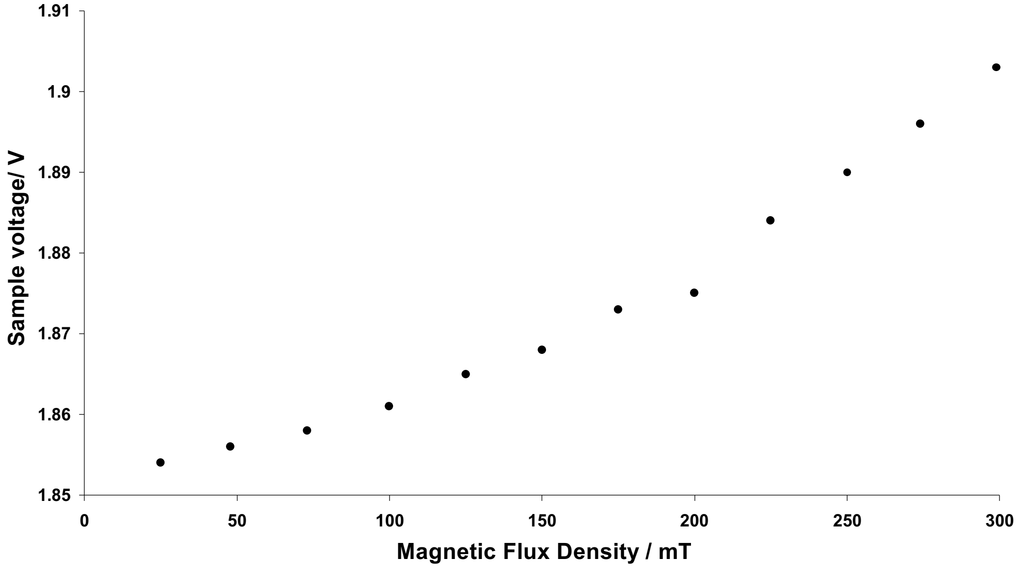


Part 2.1 n- Ge Hall voltage as a function of the current

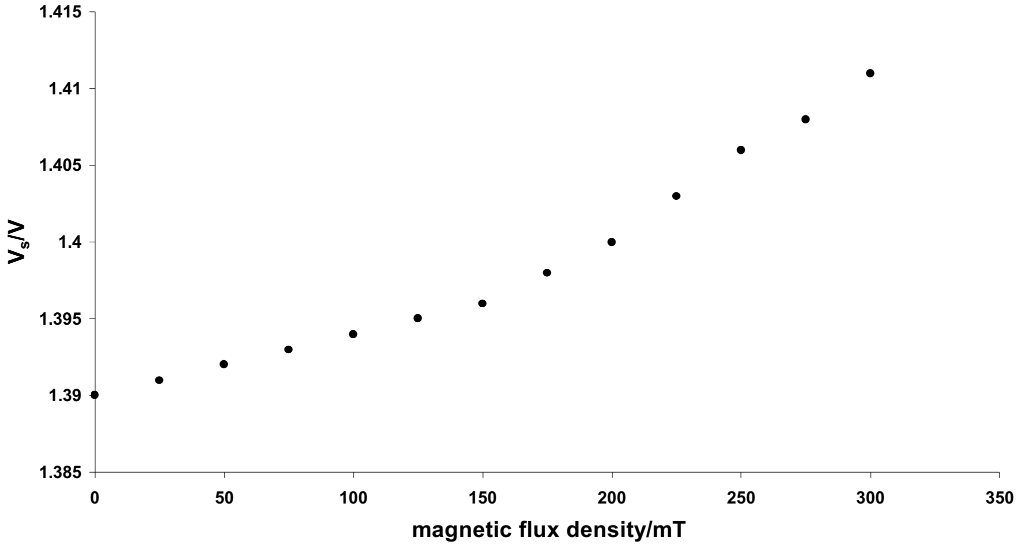
Measurements 2: Sample voltage, V_s as a function of magnetic flux density

- Control current, I was set to 30mA.
- Multimeter was connected to the sockets of the sample voltage.
- Measured the sample voltage as a function of the positive magnetic flux density up to 300mT.
- The graph (below) Sample voltage, V_s as a function of magnetic flux density was obtained for p-type Ge and n-type Ge.
- Graphs below show a non linear (quadratic) change in resistance with increase in field strength. This is related to the mean free path of the carriers.

Part 2.2 p- Ge Sample voltage, V_s as a fuction of the postive magnetic flux densit



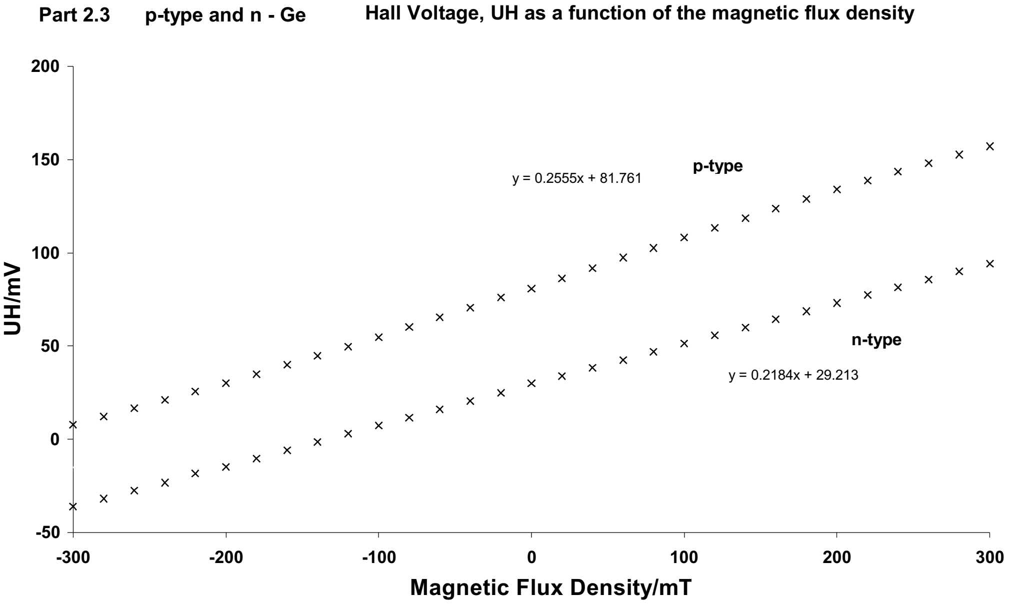
Part 2.2 n - Ge Sample voltage,V_s as a function of positive magnetic flux densit



Measurements 3: Hall voltage, U_H as a function of the magnetic flux density

- The current was set to 30 mA.
- The multimeter was connected to the sockets of the hall voltage (U_H) on the module.

- I determined the Hall voltage as a function of the magnetic flux density. With magnetic flux ranging -300mT to 300mT in steps of-20 mT.
- Started with -300 mT by changing the polarity of the coil-current and increase the magnetic flux density. At the zero point, I had to change the polarity.
- The straight line graph (below) of Hall voltage, U_H as a function of the magnetic flux density was obtained for p-type Ge and n-type Ge.



- The Hall Coefficient R_H is given by, $R_H = \frac{U_H}{B}\frac{d}{I}$. So from the gradient of the graphs I determined the Hall Coefficient as
- $R_H = 0.2555$ for p-type
- $R_H = 0.2184$ for n-type
- I calculated σ_o for the n- type Ge and the p-type Ge by using the equation

- $$\sigma = \frac{1}{\rho} = \frac{l}{A}\frac{I}{V_s}$$

- V_s at room temperature for p-type Ge = 171V,
- V_s at room temperature for n-type Ge = 95.5V

- σ_o for p-type = 0.0585 and n-type = 0.1047
- Using the following equations

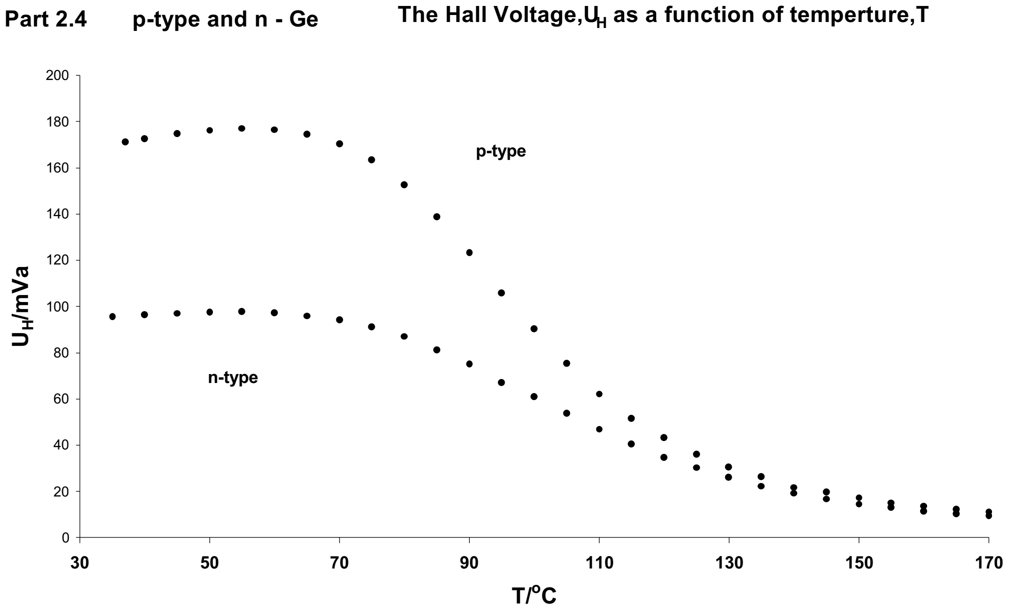
$$\mu_H = R_H \sigma_0$$

$$n = \frac{1}{eR_H}$$

- Where the elementary charge, e = -1.602 x 10^{-19}J
- I found for p-type μ_H = 0.01495, n = -2.443 x 10^{-19}
- p-type μ_H = 0.0248, n = -2.858 x 10^{-19}

Measurements 4: Hall voltage, U_H as a function of the temperature, T

- The current was set to 30 mA and the magnetic flux density to 300 mT.
- I turned on the heating coil
- I measured the Hall voltage as a function of the temperature.
- The graph (below) Hall voltage, U_H as a function of the temperature, Twas obtained for p-type Ge and n-type Ge



From the graph above, it is shown that the hall voltage decreases with increasing temperature. Because the current was kept constant, this decrease can only be caused by the increase in the number of charge carriers with caused “an associated reduction in the drift velocity, V_d”(3).

References

(1) The Fundamentals of Physics – Halliday, Resnick and Walker

(2) http://www.mtmi.vu.lt/pfk/funkc_dariniai/sol_st_phys/impurities.htm

(3) Hall effect in Germanium (work sheet) – anonymous