PHY 465 Lab Report
Hall Effect

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Abstract
When a current carrying conductor is exerted upon by an outside magnetic field, a perpendicular electric potential is induced. This is known as the Hall effect. In our experiment we tested three different samples: a positively, negatively and non-doped samples of Germanium. We used electro-magnets in this experiment as we can control the applied magnetic field more precisely by controlling the current supplied to the magnet. When exposed to a magnetic field by two electromagnets we saw and measured this Hall voltage. Some of our key findings are as follows: we measured μ_r of the iron electro-magnet to be $\mu_r = 330 \pm 3.3$, a band gap of the non-doped Germanium to be $0.48 \pm ?eV$, as well as reciprocal but equal trends in the Hall voltages for the p-doped and n-doped samples when exposed to the magnetic field.

I. **Introduction**

In this lab we will measure the Hall effect which is the basis for our modern transistors and semi-conductors. The transistor is one of the most important inventions of the 20th century. It opened the door to a whole new world of computing and lead to the inventions of integrated circuits and semiconductors that are in basically every product on the market today which critically allow for conductance to be controlled by applied electrical fields. The basis for these technologies is the Hall effect, discovered in 1879 by E. H. Hall of Johns Hopkins University. He found that "it is perhaps allowable to speak of the action of the magnet as setting up in the strip of gold leaf a new electromotive force at right angles to the primary electromotive force" (Hall, 1879). In other words there is an induced magnetic field perpendicular to and directly proportional to the the externally applied electric field.

II. **Theory**

The conductance of a semiconductor can be controlled by externally applied E fields:

$$V = IR \tag{1}$$

The integral form of current flow gives us:

$$j = \sigma E = E/\rho \tag{2}$$

Where $j = I/A$, A is the cross-sectional area of the object, E is the electric field, σ is conductivity and $\rho = 1/\sigma$ is the resistivity. Naturally following from this, along a length L we can say:

$$I = jA = \sigma EL\frac{A}{L} = GV \tag{3}$$

Since Electrons are Fermions they are incapable of occupying the same space, the arising range of energies with no existing quantum states is called the "band gap", the occupation of of states is descriped by:

$$F(E) = \frac{1}{exp\left(\frac{E-E_F}{kT}\right) + 1} \tag{4}$$

We can also estimate the band gap by linearizing the temperature dependence and using the band gap energy E_g as a function of $1/T$:

$$b = -\frac{E_g}{2k_B} \tag{5}$$

One of the primary equations we will need is Ampere's Law in media (and for solenoid):

$$B = \mu n I \tag{6}$$

The electromagnetic field intensity H can be found by:

$$H = nI\hat{z} \tag{7}$$

Where n is the turn density (number of turns per unit length N/L) and I is the current. This can then be related to the magnetic field B through permittivity μ:

$$B = \mu H = \mu n I = \mu_r \mu_0 \frac{N}{L} I \tag{8}$$

Where μ is the ratio between the permittivity of the material μ_r and the permittivity of free space μ_0.
The hall coefficient for the p-type chip ($p >> n$):

$$R_H = \frac{1}{ep} \tag{9}$$

And since p n n_i we can rearange for the density of charge carriers:

$$n = \frac{1}{R + He} \tag{10}$$

Through this the Hall voltage takes the form:

$$V_x = R_H J_y B_z W \tag{11}$$

We will also need the equation of conductivity in this lab

$$\sigma = e(\mu_n n + \mu_p p) \tag{12}$$

Finally the mobility of a charge carrier can be measured directly thorugh magneto-resistance where the change in resistivity is given by:

$$\frac{\Delta\rho}{\rho} = \mu_{n/p}^2 B^2 \tag{13}$$

III. Experimental Procedure

In this experiment we followed the standard steps outlined in the lab document provided by Arizona State University. Sketches and notes in appendix.

- Log-in to computer, following is instructions for the computer:
  - Launch **Hall_Effect_v3a** file from Student folder.
  - In the program click the arrow to begin collecting data.
  - Stop button will end collection.
  - Data will be saved to: *c:\User\Puclic\MyDat.txt*
  - Be sure to move file as the file will be overwritten otherwise.

1.) Remove front post and plate from the setup to gain access to the chip containing the sample.

2.) Remove chip, we will be running calibration without a sample.

3.) Place 4mm spacer block under chip.

4.) Reconstruct with the spacer block in place.

5.) Slowly and steadily increase the current from 0A to 4A and then back to 0A.

6.) Swap banana plugs to reverse polarity (**Ensure the voltage is at 0 before swapping**) and repeat last step.

7.) Do this process for each spacer block, increasing in size each time until you reach 20mm.

8.) Once calibrated, insert p-Ge chip into device (can find the chip type printed on the front) and replace the spacer block with 10mm.

9.) With the p-Ge chip in, to measure the Hall voltage vs magnetic field, increase the current from 0A to 4A and back to 0A (do for 3 trials).

10.) Next, to measure the temperature vs voltage, slowly turn the voltage up in several steps waiting 1s at each step.

11.) repeat steps 8-10 when the n-Ge and i-Ge chips.

IV. Results

Using eq. 8 we find that the calculated B field (assumed μ_r was large but unknown) when compared to the measured B field is around a factor of 9 (consistent with the fit found in Fig. 1) different as shown by the following measurements for the pGe chip at $I = 2.523$:

Amps	Calculated B	Observed B
2.523 ± 0.0005	0.2238 ± 0.0004	2.095 ± 0.0005

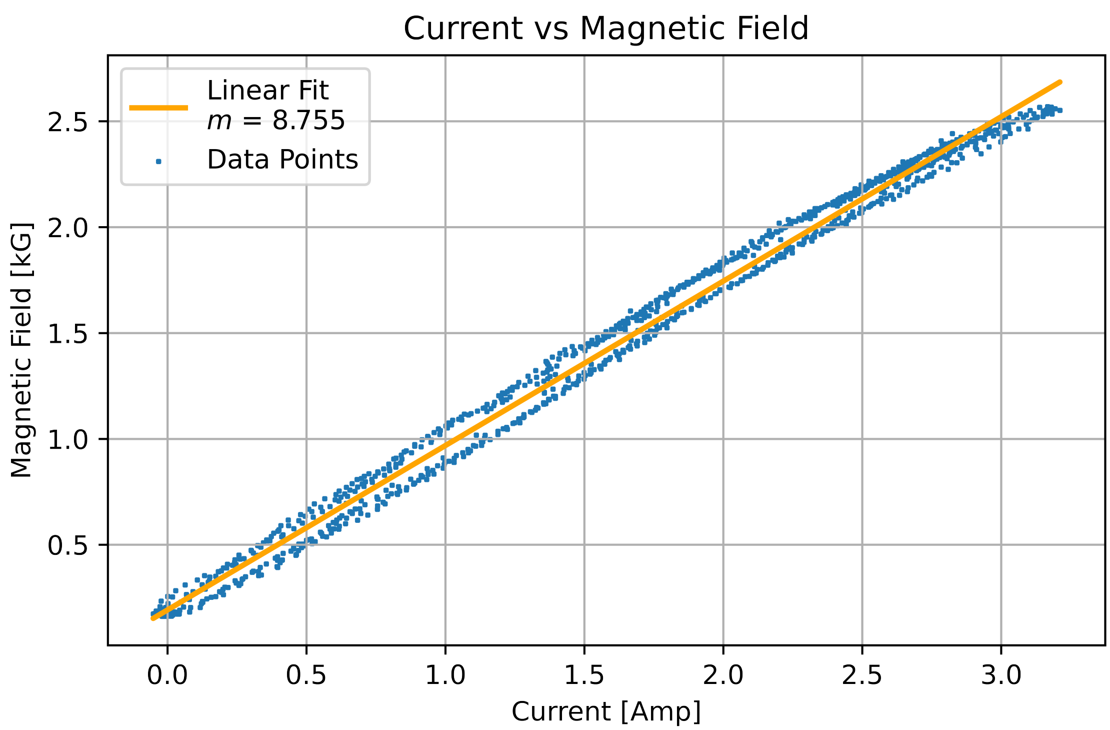


Figure 1: Magnetic field as a function of current. For the fit we calculated what the magnetic field would be if an air coil was used and allowed the slope to be a multiple of this value. This gives us a fairly reasonable estimate for how much stronger the observed field is over the expected. Further more we can estimate μ_r for the iron by looking at the ration of the electromagnet $L = 1.0H$ to an air coil $30mH$ which should relate directly to the permeability of the iron. We find this to be $\mu_r = 330 \pm 3.3$.

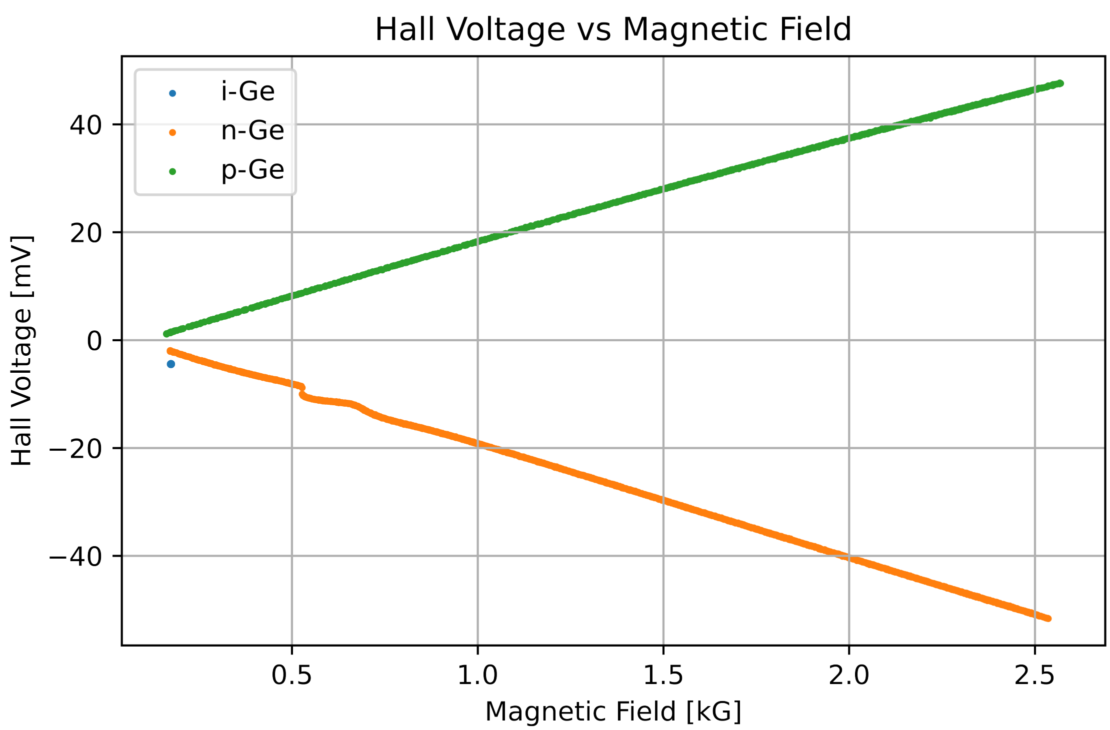


Figure 2: Hall voltage vs magnetic field for all 3 samples. The i-Ge sample does not show any effect while the p-Ge and n-Ge samples both show increasingly strong and reciprocal Hall voltages with increasing magnetic field strength.

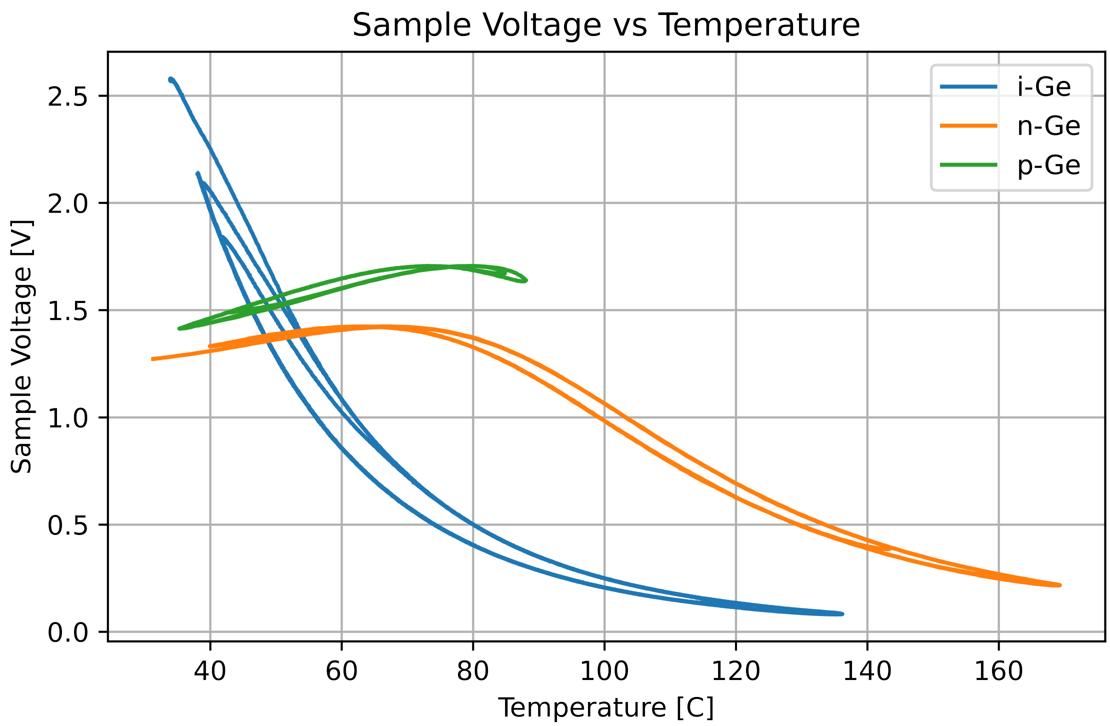


Figure 3: Sample voltage vs temperature for all 3 samples. The i-Ge sample has the most apparent relationship with temperature, as the temperature increases the voltage drops rapidly.

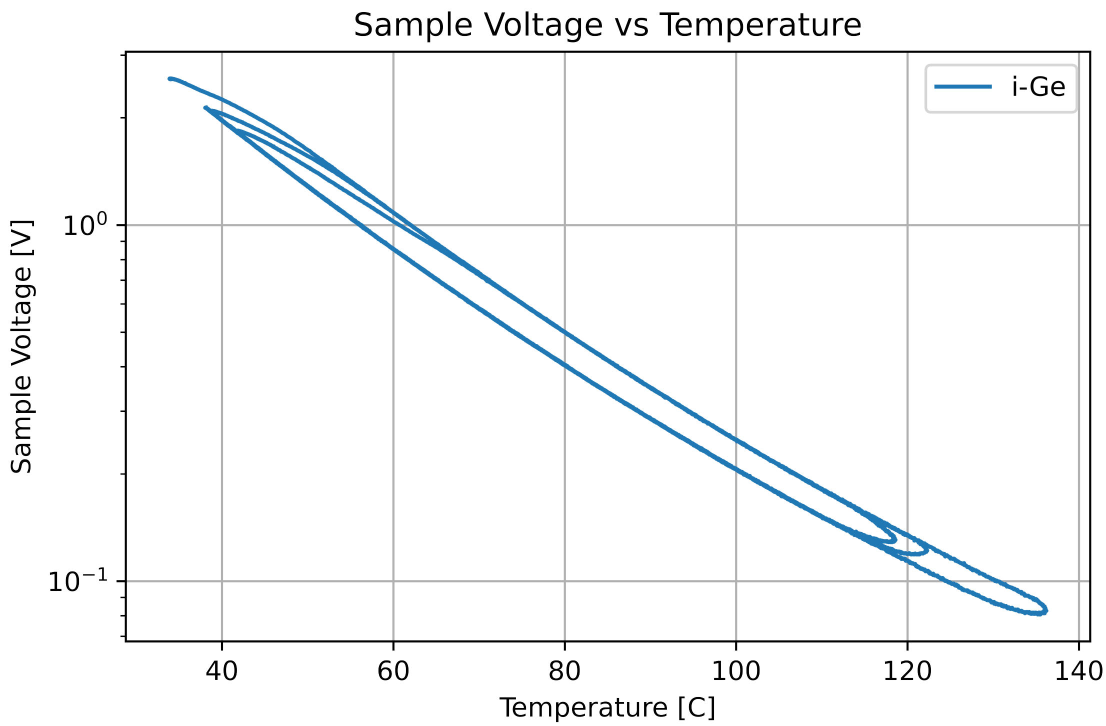


Figure 4: Linearized plot of sample voltage vs temperature for the i-Ge sample. Fitting a slope to this line we can find the gradient which can then be plugged in for b in eq. 5. Solving for the band gap energy E_g gives us a band gap of $0.48 \pm ?eV$

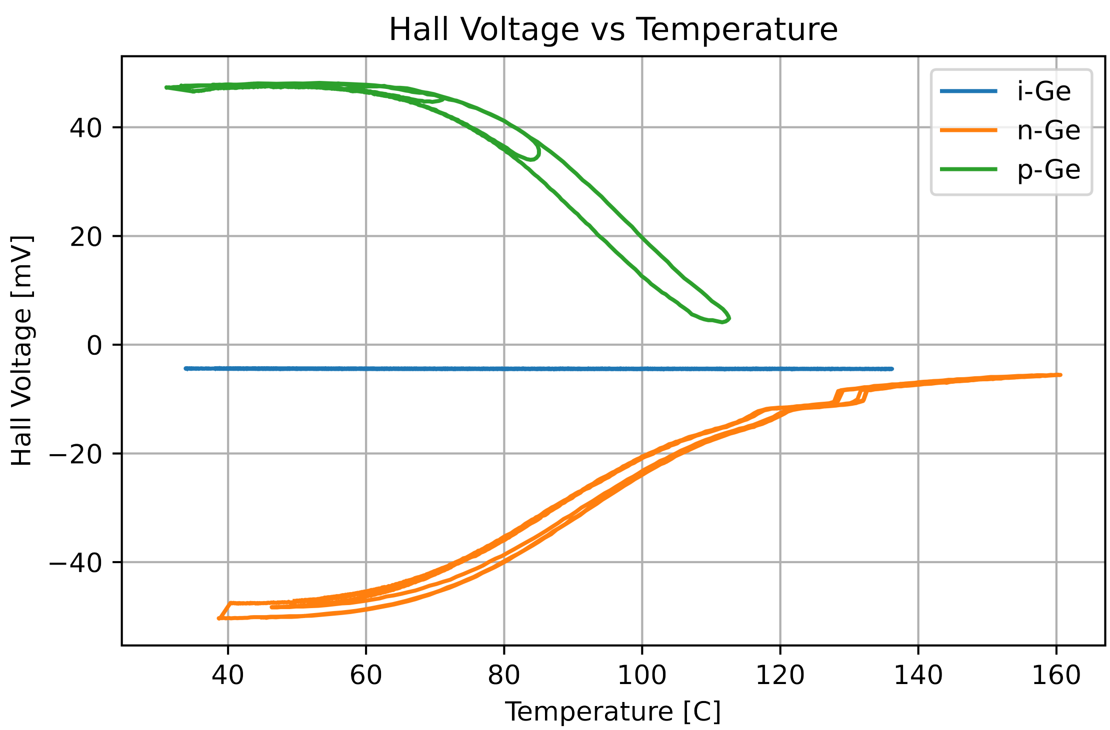


Figure 5: Hall voltage vs temperature for all 3 samples. The p-Ge sample was cut a bit short, however if we follow the trend of the n-Ge the p-Ge sample the p-Ge would continue to asymptotically approach the Hall voltage of the i-Ge sample. Looking at the equation for conductivity (eq. 12) we will be multiplying be the charge of an electron which is a negative number, resulting in the p-Ge sample tending towards negative as well.

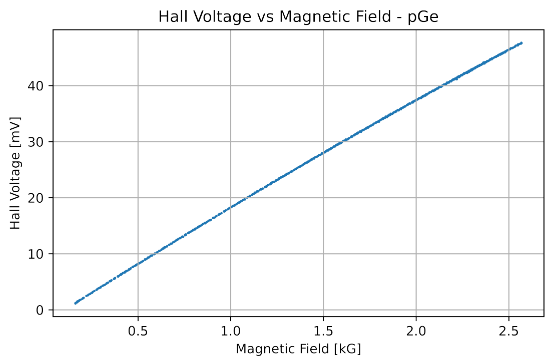
V. **Discussion**

In this lab we saw a linear relationship between the applied magnetic field to the perpendicularly induced electric potential known as the Hall voltage, validating the Hall effect. From our i-Ge data we were able to estimate a band gap of $0.48eV$ compared to the theoretical value of $0.66eV$, this gives us a experimental error of 27%. I am confident in the results of the experiment as the data looks correct and consistent with expected behaviour so I expect that this error is likely due to a mistake in the calculation of the band gap. The error in our other measurements, such a μ_r are likely due to the limitations of the measuring equipment or human error in turning the knob for the current supply.

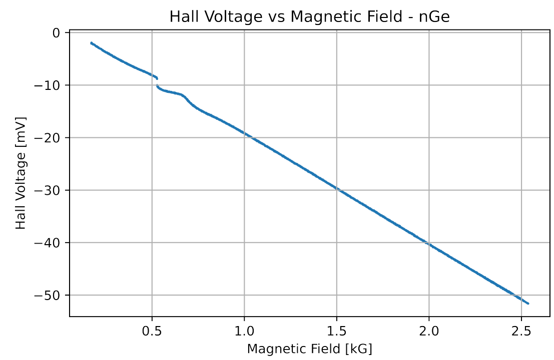
VI. **Reference**

1. Hall, E. H. "On a New Action of the Magnet on Electric Currents." *American Journal of Mathematics*, vol 2, no. 3 (1879): 287–92. https://doi.org/10.2307/2369245.
2. Hall Effect Lab Document, Arizona State University Department of Physics

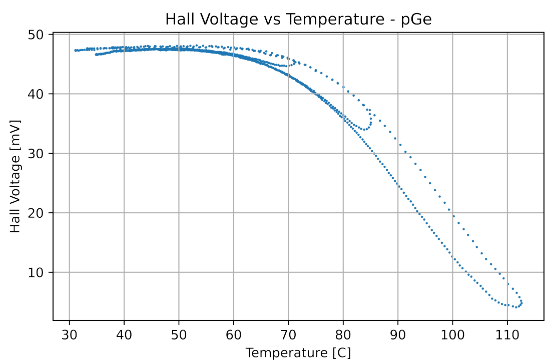
VII. **Appendix**



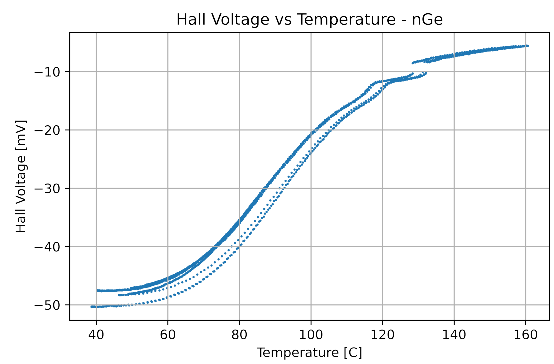
(a) Appendix 1.1



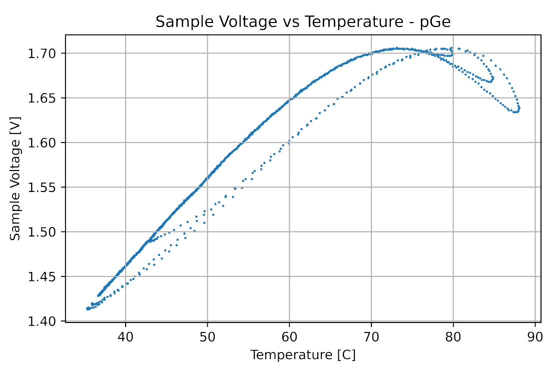
(b) Appendix 1.2



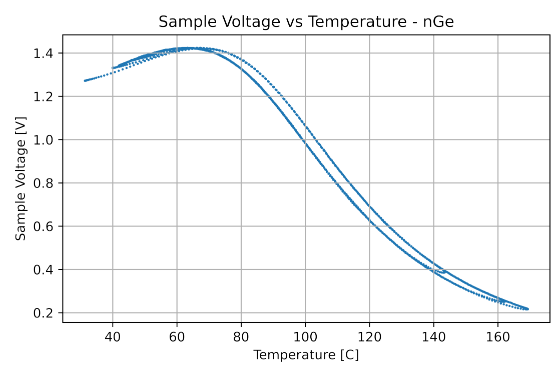
(c) Appendix 1.3



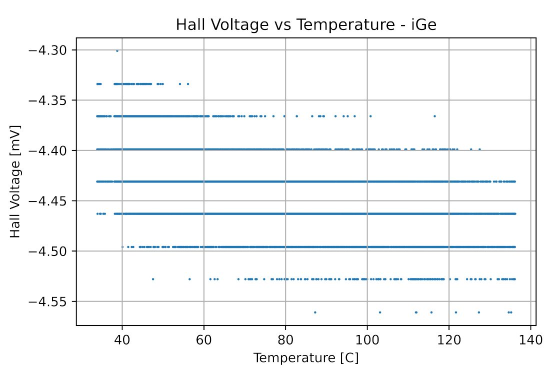
(d) Appendix 1.4



(e) Appendix 1.5



(f) Appendix 1.6



(g) Appendix 1.7

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Hall Effect

← remove front plate to get sample chip (drawing below)

Switch ~~a~~ on back of power supply

Chip w/ sample
↓

Launch file from Student folder
Hall_Effect_v3a

In ~~the~~ program
Start button
→

If you go into code interface don't hit save

data saved to:
C:\User\Public\MyDat.txt

Will overwrite if not moved, autosaves when done collecting

Sample Volt: Driving voltage

Hall Volt: Measured

Dwell time: time between samples

Don't set amps over 4!

Don't leave @ 4 for more than a few sec

Using spacer blocks set gap to

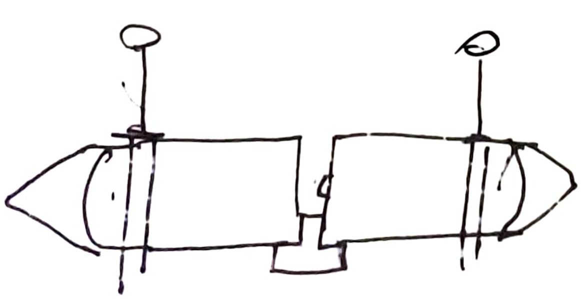
3 mm

Smallest is 2 mm

Start w/ next

g = 4.4 mm ± 0.05

reconstruct w/ spacer block in place.

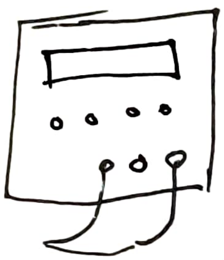


Ran 4.4mm ± 0.5 no sample
3 times

Ran again doing 3 @ once

on left power supply

Swapped banana plugs and repeat



↑ these two

For step d repeat w/ dif gap sizes

g = 9.25 ± 0.05

g = 14.65 ± 0.05

g = 19.95 ± 0.05

Calibration finished

Now Run w/ sample Ge-p

3 trials

For temp do in 1s intervals on right power supply

Repeat for Ge-n & Ge-i