Hall effect and magnetoresistance in semiconductors

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This experiment primarily deals with the study of the phenomena of Hall effect and magneto-resistance in semiconductors. First we explore the Drude model to lay down the foundation for the concepts and origin of Hall voltage and magneto-resistance and then using the well-known instrumentation like the four-probe, we establish various results. We determine the Hall coefficients of Bi, p-Ge and n-Ge and its relation to carrier density and carrier mobility, which are also determined for Bi. The unusual case of Bi is especially studied theoretically and experimentally. Then the magneto-resistance of Bi and n-Ge is determined and several plots are studied and results are drawn regarding them.

There is nothing in the world except empty curved space. Matter, charge, electromagnetism, and other fields are only manifestations of the curvature of space.

John Wheeler

I. INTRODUCTION

When a current-carrying conductor is placed in a magnetic field perpendicular to the current direction, a voltage develops transverse to the current. This voltage was first observed in 1879 by Edwin Hall and this effect is called *Hall Effect*.

The Hall effect has since led to a deeper understanding of the details of the conduction process. It can yield the density of the charge carriers as well as their sign. In simple metals, the density of carriers is an integer multiple of the density of atoms; this indicates that each atom donates a fixed number of electrons to the conduction process. In more complex metals such as bismuth, the conduction based has a small overlap with the valence band, which then contributors a very small number of electrons to the conduction band loading to very low carrier density.

The first part of the experiment concerns with study of the Hall effect in Bismuth, n-type Germanium and p-type Germanium. The second part deals with the phenomena of magnetoresistance, which follows from the concept of carrier mobility.

It is noticed that the resistance of a sample changes when the magnetic field is turned on. The *magneto-resistance* is the property of a material to change the value of its electrical resistance when an external magnetic field is applied to it. The effect was first discovered by William Thomson (more commonly known as Lord Kelvin) in 1856.

Magneto-resistance, is due to the fact that the drift velocity of all the carriers is not same, and the mechanism of which will be understood in depth using the **Drude model** later in the theory section.

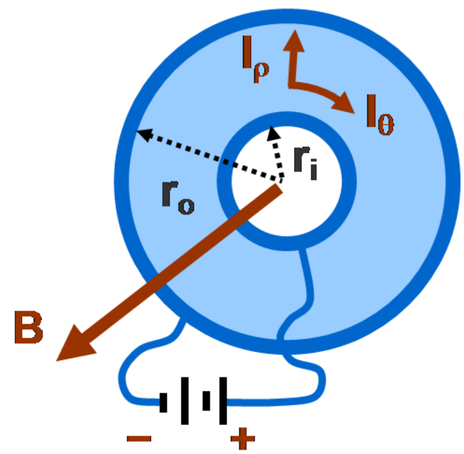

FIG. 1. Corbino disc. With the magnetic field turned off, a radial current flows in the conducting annulus due to the battery connected between the (infinite) conductivity rims. When a magnetic field along the axis is turned on (B points directly out of the screen), the Lorentz force drives a circular component of current, and the resistance between the inner and outer rims goes up. This increase in resistance due to the magnetic field is called magnetoresistance.

II. AIM

- To study the Hall effect and determine the Hall coefficient at ambient temperature for various samples of semiconductors.
- To study the magneto-resistance of various samples of semiconductors.

III. APPARATUS

The apparatus used throughout the experiment is:

1. Hall Probe (Bismuth),
2. Four probe arrangement,
3. Samples of the semiconductors used in the experiment (Bi, n-Ge, p-Ge)

4. Constant Current Source, CCS-01,
5. Digital Microvoltmeter, DMV-001,
6. Electromagnet, Model EMU-75,
7. Constant Current Power Supply, DPS-175,
8. Digital Gaussmeter, DGM-102,
9. Hall Probe Stand

IV. EXPERIMENTAL SET-UP

A. Hall Probe (Bismuth)

Bismuth strip with four spring type pressure contacts is mounted on a sunmica decorated bakelite strip Four leads are provided for connections with measuring devices.

B. Constant Current Source, Model : CCS-01

It is an IC regulated current generator to provide a constant current to the outer probes irrespective of the changing resistance of the sample due to change in temperatures. The basic scheme is to use the feedback principle to limit the load current of the supply to preset maximum value. Variations in the current are achieved by a potentiometer included for that purpose. The supply is a highly regulated and practically ripples free *DC* source. The constant current source is suitable for the resistivity measurement of thin films of metals/ alloys and semiconductors like germanium.

C. DC Microvoltmeter, Model DMV-001

Digital Microvoltmeter, DMV-001 is a very versatile multipurpose instrument for the measurement of low *DC* voltage. It has 5 decade ranges from 1 mV to 10 V with 100% overranging. This instrument uses a very well designed chopper stabilized IC amplifier. This amplifier offers exceptionally low offset voltage and input bias parameters, combined with excellent speed characteristics.

D. Electromagnet, EMU-75

The following are the specifications of EMU-75 unit:

- *Field intensity*: 11,000 $\pm$ 5% G in an air-gap of 10 mm. Air-gap is continuously variable upto 100 mm with two way knobbed wheel screw adjusting system.
- *Pole pieces*: 75 mm diameter. Normally flat faced pole pieces are supplied with the magnet.
- *Energising coils*: Two. Each coil is wound on non-magnetic formers and has a resistance of 12 ohms approx.
- *Yoke material*: Mild steel
- *Power requirement*: 0 - 100 V @ 3.5 A if connected in series; 0 - 50 V @ 7.0 A if connected in parallel.

E. Constant Current Power Supply, DPS-175

The present constant current power supply was designed to be used with the electromagnet, Model EMU-75. The current requirement of 3.5 amp/coil, i.e. a total of 7 Amp was met by connecting six closely matched constant current sources in parallel. In this arrangement the first unit works as the 'master' with current adjustment control. All others are 'slave' units, generating exactly the same current as the master.

F. Four Probes Arrangement

It has four individually spring loaded probes. The probes are collinear and equally spaced. The probes are mounted in a teflon bush, which ensure a good electrical insulation between the probes. A teflon spacer near the tips is also provided to keep the probes at equal distance. The probe arrangement is mounted in a suitable stand, which also holds the sample plate and RTD sensor. This stand also serves as the lid of PID Controlled Oven. Proper leads are provided for current, Voltage and Temp. measurement with their universal connectors. For current measurement there is three pin connector which can be connected to the CCS-01/ LCS-02 as per requirement of sample. For voltage measurement BNC connector is used connected to DMV-001 unit. For temperature measurement, a two pin connector is provided for connection with PID- Controlled oven unit PID-200 at connector marked as Temperature Sensor. Three levelling screws are provided in Four Probe arrangement by which we can adjust the level of plateform to make it horizontal. A probe holding screw is provided at the collar of the arrangement. Initially it should be in loose position, to allow free movement of Probe Pipe. After placing the sample the Probe Pipe should be lowered so that all four pins touches the sample. The pipe is further pressed very lightly so that the assured firm contact is made of all Four Pins with the sample. The probe holding screw is tightened at this position making the arrangement ready to use.

G. Digital Gaussmeter, Model DGM-102

The Gaussmeter operates on the principle of Hall Effect in semiconductors. A semiconductor material carrying current develops an electro-motive force, when placed in a magnetic field, in a direction perpendicular to the direction of both electric current and magnetic field. The magnitude of this e.m.f. is proportional to the field intensity if the current is kept constant, this e.m.f. is called the Hall Voltage.

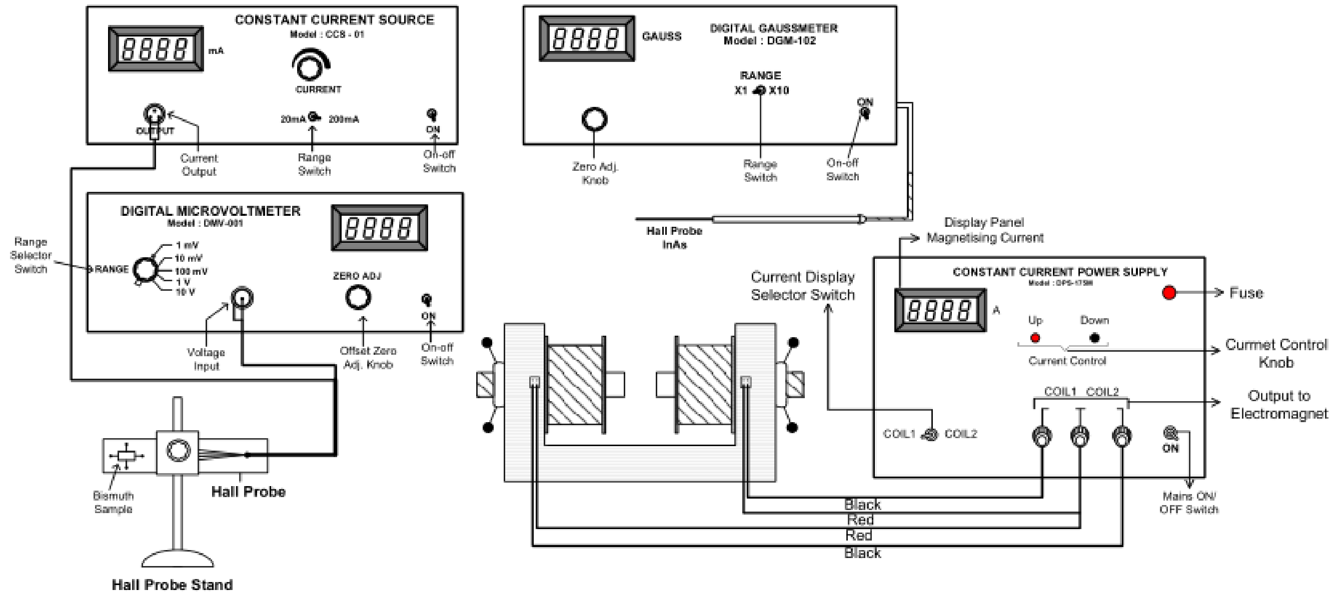

FIG. 2. Panel diagram for Hall effect experiment

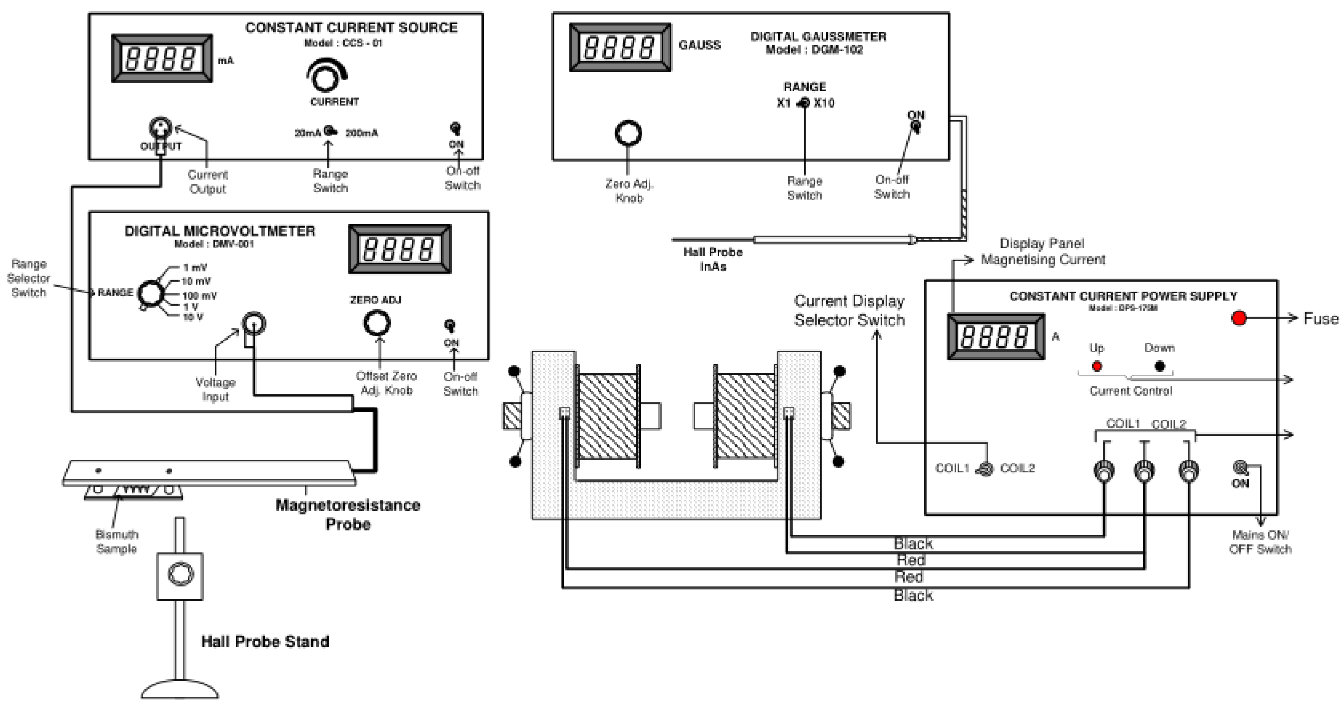

FIG. 3. Panel diagram for magneto-resistance experiment

V. THEORY

A. The Hall Effect

A static magnetic field has no effect on charges unless they are in motion. When the charges flow, a magnetic field directed perpendicular to the direction of flow produces a mutually perpendicular force on the charges. When this happens, electrons and holes will be separated by opposite forces. They will in turn produce an electric field ($\boldsymbol{E_h}$) which depends on the cross product of the magnetic intensity, $\boldsymbol{H}$, and the current density, $\boldsymbol{J}$. The situation is demonstrated in figure (7).

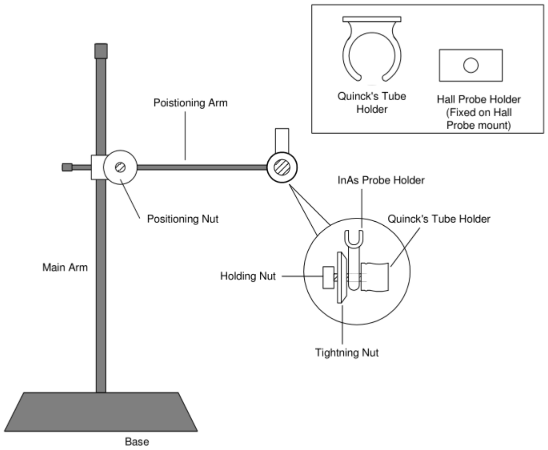

FIG. 4. Multi-purpose stand used in the experiments

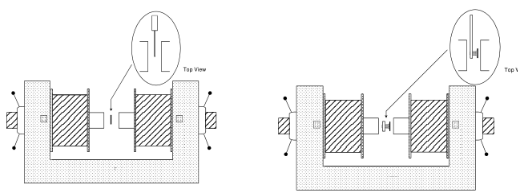

FIG. 5. The placing of Gaussmeter Hall probe in electromagnet (left) and of magneto-resistance sample in electromagnet (right)

$$\boldsymbol{E_h} = R\boldsymbol{J} \times \boldsymbol{H} \tag{1}$$

where R is called the Hall coefficient.

Now, let us consider a bar of a semiconductor, having dimensions, x, y and z. Let $\boldsymbol{J}$ be directed along X and $\boldsymbol{H}$ along Z, then $\boldsymbol{E_h}$ will be along Y, as in figure (9). Then,

$$R = \frac{V_h/y}{JH} = \frac{V_h \cdot z}{IH} \tag{2}$$

where V_h is the Hall voltage appearing between the two surfaces perpendicular to y and $I = Jyz$.

In general, the Hall voltage is not a linear function of magnetic field applied, i.e. the Hall coefficient is not generally a constant, but a function of the applied magnetic field. Consequently, interpretation of the Hall Voltage is not usually a simple matter. However, it is easy to calculate this (Hall) voltage

FIG. 6. Complete experimental setup

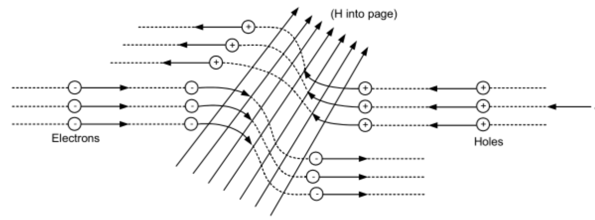

FIG. 7. Carrier seperation due to a magnetic field

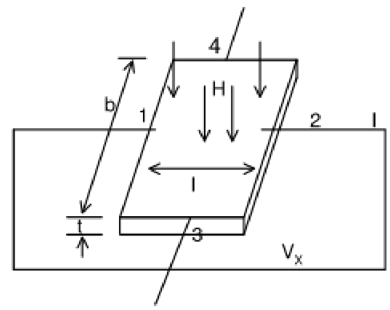

FIG. 8. Schematic arrangement for the measurement of Hall Effect of a crystal

if it is assumed that all carriers have the same drift velocity. We will do this calculation for metals and degenerate (doped) semiconductors.

The magnetic force on the carriers is $\boldsymbol{E_m} = e(\boldsymbol{v} \times \boldsymbol{H})$ and is compensated by the Hall field $\boldsymbol{F_h} = e\boldsymbol{E_h}$ where $\boldsymbol{v}$ is the drift velocity of the carrier. The current density is $\boldsymbol{J} = qn\boldsymbol{v}$. From here we get

$$R = \frac{E_h}{JH} = \frac{v \cdot H}{qnvH} = \frac{1}{nq} \tag{3}$$

From this equation[1], it is clear that the sign of Hall coefficient depend upon the sign of q. Also for a fixed magnetic field and input current, the Hall voltage is proportional to $1/n$ or its resistivity. The conductivity of the material is $\sigma = nq\mu$, where μ is the mobility of the charge carriers.

Thus we see that the Hall coefficient, in conjunction with resistivity measurements, can provide information on carrier densities, mobilities, impurity concentration and other values.

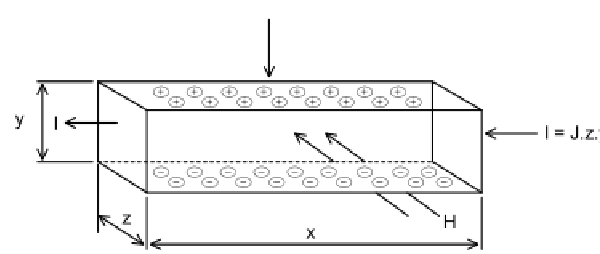

FIG. 9. Sample for studying Hall Effect

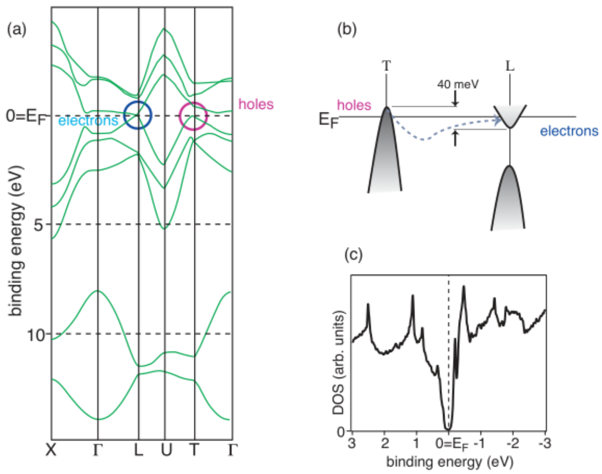

FIG. 10. Electronic structure of Bismuth. (a) Bulk band dispersion in different directions of the Brillouin zone (b) Schematic band structure of the bands crossing the Fermi energy. (c) Density of states.

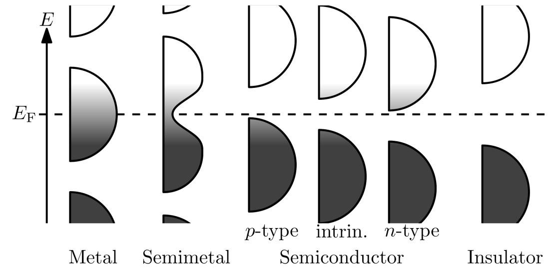

FIG. 11. Filling of the electronic states in various types of materials at equilibrium. Here, height is energy while width is the density of available states for a certain energy in the material listed. The shade follows the Fermi–Dirac distribution (black = all states filled, white = no state filled). In metals and semimetals the Fermi level EF lies inside at least one band. In insulators and semiconductors the Fermi level is inside a band gap; however, in semiconductors the bands are near enough to the Fermi level to be thermally populated with electrons or holes.

B. Hall effect in Bismuth

Bi atoms have 5 valence electrons, two s electrons and 3 p electrons. The bulk crystal structure of Bi is a bit complicated but for us the only important thing is that there are two atoms per unit cell. This makes 10 electrons per unit cell. Since this is an even number, Bi could technically be a semiconductor but we need to keep in mind that having an even number of valence electrons per unit cell is only a necessary criterion for having a semiconductor. It is not sufficient. In the case of Bi, we have an electronic situation that is very close to being a semiconductor - but not quite.

This is illustrate in figure 10(a) which shows the band structure of Bi. The two lowest bands can be viewed as s-derived. The are well separated from the higher p-type bands and fully occupied by the 4 s electrons in the unit cell. this leaves 6 p electrons which could exactly fill three more bands. A superficial look on the band structure appears to confirm this. When zooming in as schematically done in Figure 10(b), however, we see that the upper “valence band” crosses the Fermi energy the T point of the Brillouin zone whereas the lowest “conduction band” drops below the Fermi energy at the L point. The valence band is thus almost completely filled apart from a very small concentration of holes and the conduction band is completely empty apart from a very small concentration of electrons. The total electron and hole concentration must the the same, of course, so that the Bi remains charge neutral. An impressive illustration of the small carrier concentration is shown in density of states shown Figure 10(c). At first glance the density of states appears to go to zero near the Fermi energy such that a gap is formed. But this is so only superficially. The density of states does not actually go to zero. It is just very small.

C. Magneto-resistance in semiconductors

With the magnetic field on; the Hall voltage compensates exactly the Lorentz force for carriers with average velocity; slower carriers will be over compensated and faster ones undercompensated, resulting in trajectories that are not along the applied field. This results in an effective decrease of the mean free path and hence an increase in resistivity. Here the above referred symbols are defined as: v = drift velocity; E = applied electric field; t = thickness of the crystal; H = Magnetic field

D. Magneto-resistance in Bismuth

Bismuth is a semimetal. A semimetal is a material with a very small overlap between the bottom of the conduction band and the top of the valence band. Because of the slight overlap between the conduction and valence bands, semimetal has no band gap and a negligible density of states at the Fermi level. A metal, by contrast, has an appreciable density of states at the Fermi level because the conduction band is partially filled. Unlike metals, semimetals have both type of charge carriers viz. electrons and holes.

E. Negative Magneto-resistance

In the ferromagnetic metals a negative character of the magnetoresistance due to the electron-spin scattering arises from the following origin: The magnetic field increases the effective field acting on the localized spins and suppresses the fluctuation of spins in space and time (also called spin disorders), which leads to the decrease of the resistivity. It has been found that magneto-resistance is is positive in the anti-ferromagnetic state, while it is negative in the ferromagnetic and paramagnetic states.

VI. OBSERVATIONS

The Hall voltage reading corresponding to different magnetic field values at ambient temperature for Bi is tabulated in table (I), for p-Ge in table (II) and for n-Ge in table (III). The data of magneto-resistance for Bi is tabulated in table (IV) and for n-Ge in table (V). The $V_h \sim H$ plots for Bi, p-Ge and n-Ge are given in figures (12), (13) and (14) respectively. The $\Delta R/R \sim H$ plots for Bi and n-Ge are given in figures (17) and (18) respectively and their corresponding logarithmic plots are given in figures (15) and (16) respectively. Additionally following observations were made:

1. Ambient temperature $T = 23°\mathrm{C}$
2. Probe current for Bi when studying Hall's effect $I = 190\,\mathrm{mA}$.
3. Thickness of Bi sample when studying Hall's effect $z = 0.5\,\mathrm{mm}$.
4. Probe current for p-Ge when studying Hall's effect $I = 0.98\,\mathrm{A}$.
5. Thickness of p-Ge sample when studying Hall's effect $z = 0.5\,\mathrm{mm}$.
6. Probe current for n-Ge when studying Hall's effect $I = 1.2\,\mathrm{A}$.
7. Thickness of n-Ge sample when studying Hall's effect $z = 0.5\,\mathrm{mm}$.
8. Probe current for Bi when studying magneto-resistance $= 195.8\,\mathrm{mA}$.
9. Resistance without magnetic field for Bi $R = 7.5587 \times 10^{-4}\,\Omega$.
10. Probe current for n-Ge when studying magneto-resistance $I = 4\,\mathrm{mA}$.
11. Resistance without magnetic field for n-Ge $R = 43.92\,\Omega$.
12. Resistivity of Bi $\rho = 1.29 \times 10^{-4}\,\Omega\,\mathrm{cm}$.
13. Resistivity of p-Ge $\rho = 1.29 \times 10^{-4}\,\Omega\,\mathrm{cm}$.

VII. CALCULATIONS

We have, Hall coefficient

$$R = \frac{V_h z}{IH} \tag{4}$$

The slope of the $V_h \sim H$ for Bi by using the data given in table (I) is $4.23 \times 10^{-6}\,\mathrm{mV\,G^{-1}}$, for p-Ge using data given in table (II) is $0.0045\,\mathrm{mV\,G^{-1}}$ and for n-Ge using the data given in table (III) is $0.009\,35\,\mathrm{mV\,G^{-1}}$. Putting in the values we get the

TABLE I. Variance of Hall voltage with magnetic field for Bi

#	**Current** I (A)	**Magnetic field** H (G)	**Hall voltage** V_H (mV)
1	0	0	0
2	0.2	1106	-0.004
3	0.31	1556	-0.008
4	0.4	1997	-0.01
5	0.5	2490	-0.013
6	0.6	2910	-0.016
7	0.7	3370	-0.018
8	0.8	3890	-0.02
9	0.9	4320	-0.022
10	1	4770	-0.024
11	1.2	5610	-0.028
12	1.5	6790	-0.032
13	1.81	7680	-0.035
14	2.1	8340	-0.037
15	2.4	8840	-0.038
16	2.7	9240	-0.04
17	3	9590	-0.041

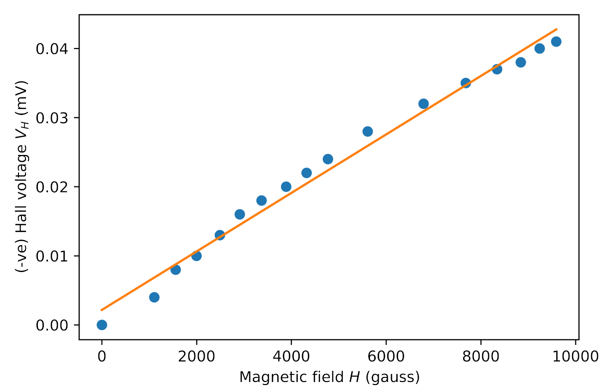

FIG. 12. $V_h \sim H$ plot for Bi

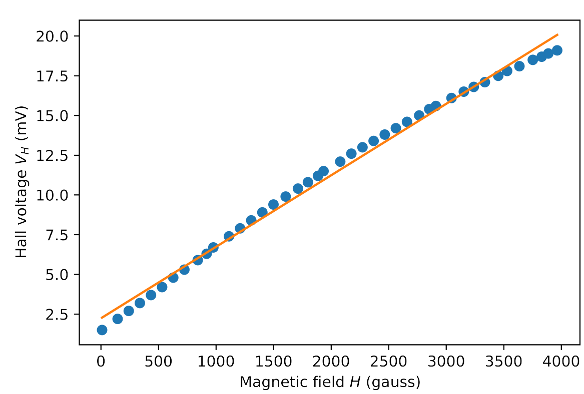

FIG. 13. $V_h \sim H$ plot for p-Ge

TABLE II. Variance of Hall voltage with magnetic field for p-Ge

#	**Current** I (A)	**Magnetic field** H (G)	**Hall voltage** V_H (mV)
1	0.01	9.669	1.5
2	0.15	145.035	2.2
3	0.25	241.725	2.7
4	0.35	338.415	3.2
5	0.45	435.105	3.7
6	0.55	531.795	4.2
7	0.65	628.485	4.8
8	0.75	725.175	5.3
9	0.87	841.203	5.9
10	0.95	918.555	6.3
11	1.01	976.569	6.7
12	1.15	1111.935	7.4
13	1.25	1208.625	7.9
14	1.35	1305.315	8.4
15	1.45	1402.005	8.9
16	1.55	1498.695	9.4
17	1.66	1605.054	9.9
18	1.77	1711.413	10.4
19	1.86	1798.434	10.8
20	1.95	1885.455	11.2
21	2	1933.8	11.5
22	2.15	2078.835	12.1
23	2.25	2175.525	12.6
24	2.35	2272.215	13
25	2.45	2368.905	13.4
26	2.55	2465.595	13.8
27	2.65	2562.285	14.2
28	2.75	2658.975	14.6
29	2.86	2765.334	15
30	2.95	2852.355	15.4
31	3.01	2910.369	15.6
32	3.15	3045.735	16.1
33	3.26	3152.094	16.5
34	3.35	3239.115	16.8
35	3.45	3335.805	17.1
36	3.57	3451.833	17.5
37	3.65	3529.185	17.8
38	3.76	3635.544	18.1
39	3.88	3751.572	18.5
40	3.96	3828.924	18.7
41	4.02	3886.938	18.9
42	4.1	3964.29	19.1

Hall coefficients as $R_{Bi} = 11.13 \times 10^{-10}\,\Omega\,\mathrm{cm}\,\mathrm{G}^{-1}$, $R_{p-Ge} = 2.29 \times 10^{-7}\,\Omega\,\mathrm{cm}\,\mathrm{G}^{-1}$ and $R_{n-Ge} = 3.90 \times 10^{-7}\,\Omega\,\mathrm{cm}\,\mathrm{G}^{-1}$.

Now the carrier density for Bi is given by

$$n = \frac{1}{Rq} \tag{5}$$

where $q = 1.6 \times 10^{-19}\,\mathrm{C}$. This gives $n = 5.61 \times 10^{21}\,\mathrm{cm}^{-3}$. The carrier mobility is given by

$$\mu = \frac{R}{\rho} \tag{6}$$

Putting the values gives us carrier mobility for Bi as $\mu = 8.63 \times 10^{-6}\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$.

TABLE III. Variance of Hall voltage with magnetic field for n-Ge

S.no	**Current** I (A)	**Magnetic field** H (G)	**Hall voltage** V_H (mV)
1	0.15	145.035	-2.1
2	0.28	270.732	-3.2
3	0.36	348.084	-4
4	0.46	444.774	-4.9
5	0.55	531.795	-5.9
6	0.66	638.154	-6.9
7	0.75	725.175	-7.7
8	0.85	821.865	-8.6
9	0.96	928.224	-9.7
10	1.02	986.238	-10.2
11	1.16	1121.604	-11.6
12	1.25	1208.625	-12.5
13	1.35	1305.315	-13.4
14	1.45	1402.005	-14.4
15	1.56	1508.364	-15.4
16	1.66	1605.054	-16.4
17	1.76	1701.744	-17.3
18	1.85	1788.765	-18.1
19	1.96	1895.124	-19.1
20	2.01	1943.469	-19.6
21	2.15	2078.835	-20.9
22	2.25	2175.525	-21.9
23	2.36	2281.884	-22.8
24	2.47	2388.243	-23.8
25	2.55	2465.595	-24.6
26	2.65	2562.285	-25.4
27	2.75	2658.975	-26.3
28	2.85	2755.665	-27.2
29	2.95	2852.355	-28.1
30	3.02	2920.038	-28.7
31	3.15	3045.735	-29.7
32	3.26	3152.094	-30.7
33	3.36	3248.784	-31.5
34	3.5	3384.15	-32.7
35	3.63	3509.847	-33.8
36	3.76	3635.544	-34.7
37	3.85	3722.565	-35.5
38	3.95	3819.255	-36.1
39	4.12	3983.628	-37.3

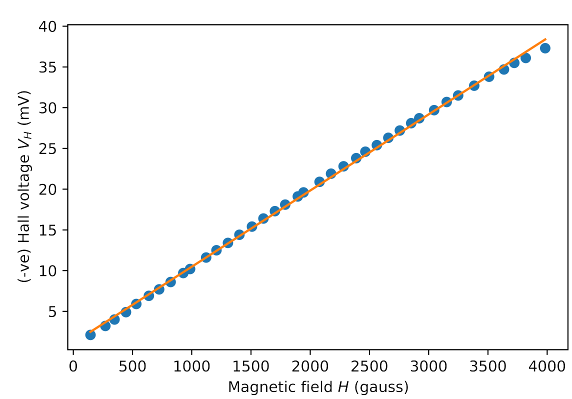

FIG. 14. $V_h \sim H$ plot for n-Ge

TABLE IV. Data for magneto-resistance for Bi

#	Magnetic field H (kG)	Voltage (mV)	R_m (mΩ)	$\Delta R/R$ (10^{-3})	$\log H$ (G)	log ($\Delta R/R$) (10^{-3})
1	0.5403	0.149	0.761	6.761	2.733	0.830
2	1.0336	0.151	0.771	20.275	3.014	1.307
3	1.3859	0.152	0.776	27.032	3.142	1.432
4	1.7617	0.153	0.781	33.788	3.246	1.529
5	1.9966	0.154	0.787	40.545	3.300	1.608
6	2.5134	0.156	0.797	54.059	3.400	1.733
7	2.9597	0.161	0.822	87.843	3.471	1.944
8	3.2886	0.163	0.832	101.356	3.517	2.006
9	3.4765	0.165	0.843	114.870	3.541	2.060
10	3.8054	0.168	0.858	135.140	3.580	2.131
11	4.1107	0.17	0.868	148.654	3.614	2.172
12	4.3691	0.172	0.878	162.167	3.640	2.210
13	4.651	0.174	0.889	175.681	3.668	2.245
14	5.0973	0.175	0.894	182.438	3.707	2.261
15	5.4497	0.176	0.899	189.194	3.736	2.277
16	5.7785	0.178	0.909	202.708	3.762	2.307
17	5.896	0.179	0.914	209.465	3.771	2.321
18	6.0134	0.181	0.924	222.978	3.779	2.348
19	6.0604	0.182	0.930	229.735	3.783	2.361

TABLE V. Data for magneto-resistance for n-Ge

#	Magnetic field H (kG)	Voltage (mV)	R_m (mΩ)	$\Delta R/R$ (10^{-3})	$\log H$ (G)	log ($\Delta R/R$) (10^{-3})
1	0.793	175.9	43.975	1.252	2.899	0.098
2	1.035	176.1	44.025	2.391	3.015	0.379
3	1.29	176.3	44.075	3.529	3.111	0.548
4	1.544	176.6	44.150	5.237	3.189	0.719
5	2.05	177.2	44.300	8.652	3.312	0.937
6	2.55	178	44.500	13.206	3.407	1.121
7	3.05	178.9	44.725	18.329	3.484	1.263
8	3.53	179.9	44.975	24.021	3.548	1.381
9	4	180.9	45.225	29.713	3.602	1.473

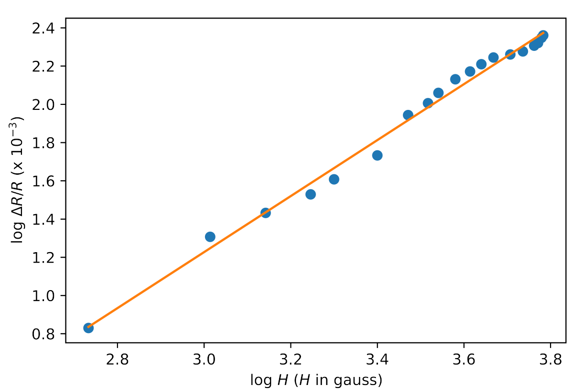

FIG. 15. $\log \Delta R/R \sim \log H$ plot for Bi

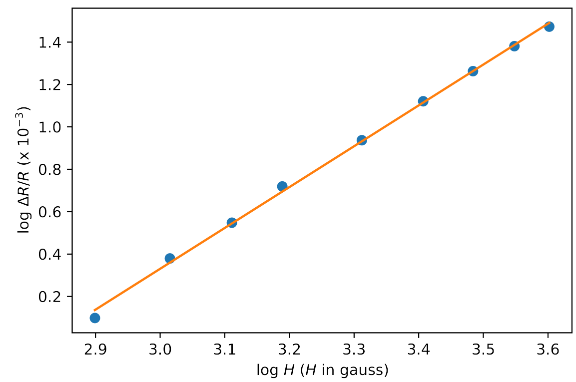

FIG. 16. $\log \Delta R/R \sim \log H$ plot for n-Ge

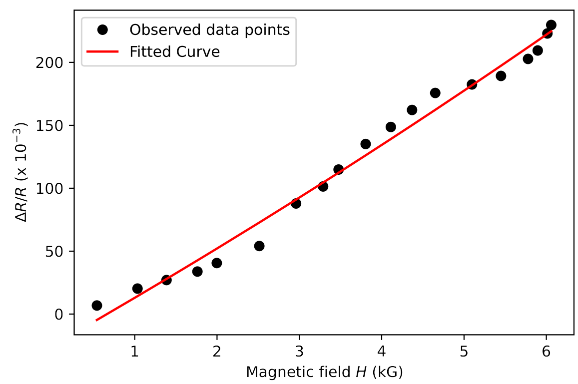

FIG. 17. $\Delta R/R \sim H$ plot for Bi

VIII. ERROR ANALYSIS

The error in Hall coefficient is given by

$$dR = \sqrt{\left(\frac{\partial R}{\partial m}\sigma_m\right)^2 + \left(\frac{\partial R}{\partial z}\sigma_z\right)^2 + \left(\frac{\partial R}{\partial I}\sigma_I\right)^2} \tag{7}$$

where m is the slope of the $V_h \sim H$ curve for the semiconductor. Now error in slope, σ_m is given by

$$\sigma_m = \sigma_y\sqrt{\frac{n}{\Delta}} \tag{8}$$

Here σ_y is the least count of V and n and Δ represent the usual summations in regression analysis. After putting the values and solving, we get error in Hall voltage for Bi $dR_{Bi} = 0.03 \times 10^{-10}\,\Omega\,\mathrm{cm}\,\mathrm{G}^{-1}$. Similarly we get $dR_{p-Ge} = 0.03 \times 10^{-7}\,\Omega\,\mathrm{cm}\,\mathrm{G}^{-1}$ and $dR_{n-Ge} = 0.02 \times 10^{-7}\,\Omega\,\mathrm{cm}\,\mathrm{G}^{-1}$.

Error in carrier density n is only due to R, and is equal to $dn = 0.17 \times 10^{21}\,\mathrm{cm}^{-3}$ and similarly, error in carrier mobility is also just due to R and is equal to $d\mu = 0.27 \times 10^{-6}\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$.

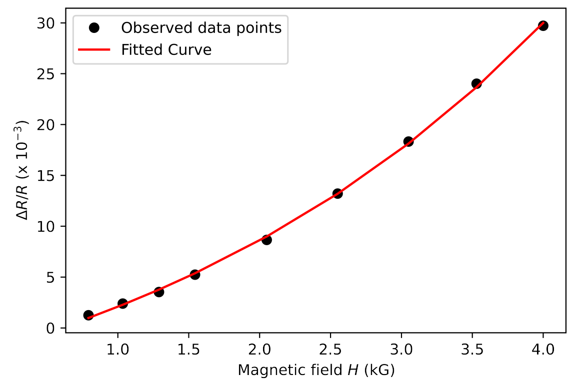

FIG. 18. $\Delta R/R \sim H$ plot for n-Ge

IX. RESULTS

1. The Hall coefficient of Bi is given by $(11.13 \pm 0.03) \times 10^{-11}\,\Omega\,\mathrm{cm}\,\mathrm{G}^{-1}$.

2. The Hall coefficient of p-Ge is given by $(2.29 \pm 0.03) \times 10^{-7}\,\Omega\,\mathrm{cm}\,\mathrm{G}^{-1}$.

3. The Hall coefficient of n-Ge is given by $(3.90 \pm 0.02) \times 10^{-7}\,\Omega\,\mathrm{cm}\,\mathrm{G}^{-1}$.

4. The carrier density for Bi is $n = (5.61 \pm 0.17) \times 10^{21}\,\mathrm{cm}^{-3}$.

5. The carrier mobility for Bi is $\mu = (8.63 \pm 0.27) \times 10^{-6}\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$.

6. The log-log graphs between magnetic field and $\Delta R/R$ were straight lines and graphs between $\Delta R/R$ and H were exponential.

X. DISCUSSIONS

1. The hall coefficient for Bismuth and n-Ge comes out as negative as was expected. This signifies the majority charge carriers are electrons.

2. The hall coefficient for p-Ge is positive as was expected. This signifies that holes are the majority charge carriers.

3. The resistance of the sample increases with the increase in the magnetic field as evident by the formula.

4. A high voltage impedance is generally needed to measure the Hall voltage.

5. The Hall voltage should be measured for both directions of current as well as magnetic field.

6. With increase in temperature, the Hall voltage falls in value and turns negative soon after.

7. Magneto-resistance is explained qualitatively using cyclotron effect in metals which devoid of magnetic moment and with spin disorder in magnetic atoms. Bismuth comes under first category.

8. The plots for magneto-resistance were obtained as expected, although the plot for Bi had an inflection point, which implies poor data.

9. The logarithmic graph follows a straight line as expected.

XI. CONCLUSIONS

1. In most cases, the results so obtained were satisfactory.

2. As the resistivity of the sample of n-Ge and p-Ge was not known, carrier mobility could not be calculated for them.

3. Error could have been obtained due to carrier injection or improper doping of the sample.

[1] Assuming that all carriers have same velocity.