

User's Manual

HALL EFFECT EXPERIMENT

Model : HEX-21
(Rev : 01/04/2010)

Manufactured by:

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ISO 9001:2008
CERTIFIED COMPANY



SAFETY INFORMATION

This Section addresses safety considerations and describes symbols that may appear on the Instrument or in the manual.

A **Warning** Statement identifies conditions or practices that could result in injury or death. A **Caution** statement identifies conditions or practices that could result in damage to the Instrument or equipment to which it is connected.

Warning

To avoid electric shock, personal injury, or death, carefully read the information in Table-1, "Safety Information," before attempting to install, use, or service the Instrument.

GENERAL SAFETY SUMMARY

This equipment is Class 1 equipment tested in accordance with the European Standard publication EN 61010-1.

This manual contains information and warnings that must be observed to keep the Instrument in a safe condition and ensure safe operation.

To use the Instrument correctly and safely, read and follow the precautions in Table 1 and follow all safety instructions or warnings given throughout this manual that relate to specific measurement functions. In addition, follow all generally accepted safety practices and procedures required when working with and around electricity.

SYMBOLS

Table 2 lists safety and electrical symbols that appear on the Instrument or in this manual.

Table 2. Safety and Electrical Symbols

Symbols	Description	Symbols	Description
	Risk of danger. Important information. See Manual.		Earth ground
	Hazardous voltage. Voltage >30Vdc or ac peak might be present.		Potentially hazardous voltage
	Static awareness. Static discharge can damage parts.		Do not dispose of this product as unsorted municipal waste. Contact SES or a qualified recycle for disposal.

Table 1. Safety Information

 **Warning**

To avoid possible electric shock, personal injury, or death, read the following before using the Instrument:

- **Use the Instrument only as specified in this manual, or the protection provided by the Instrument might be impaired.**
- **Do not use the Instrument in wet environments**
- **Inspect the Instrument in wet environments.**
- **Inspect the Instrument before using it. Do not use the Instrument if it appears damaged.**
- **Inspect the connecting lead before use. Do not use them if insulation is damaged or metal is exposed. Check the connecting leads for continuity. Replace damaged connecting leads before using the Instrument.**
- **Whenever it is likely that safety protection has been impaired, make the Instrument inoperative and secure it against any unintended operation.**
- **Have the Instrument serviced only by qualified service personnel.**
- **Always use the power cord and connector appropriate for the voltage and outlet of the country or location in which you are working.**
- **Never remove the cover or open the case of the Instrument before without first removing it from the main power source.**
- **Never operate the Instrument with the cover removed or the case open.**
- **Use only the replacement fuses specified by the manual.**
- **Do not operate the Instrument around explosive gas, vapor or dust.**
- **When servicing the Instrument, use only specified replacement parts.**
- **The equipment can remain Switched on continuously for five hours**
- **The equipment must remain Switched off for at lease fifteen minutes before being switched on again.**
- **The equipment is only for the intended use**
- **Use the equipment only as specified in this manual.**

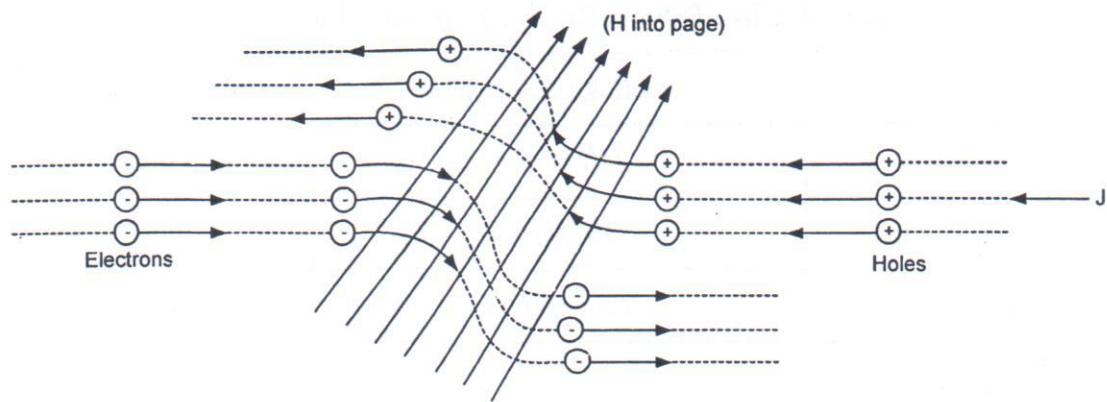


Fig. 1 : Carrier separation due to a magnetic field

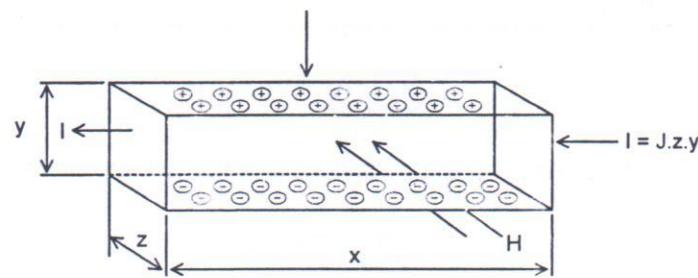


Fig. 2 : Sample for studying Hall Effect

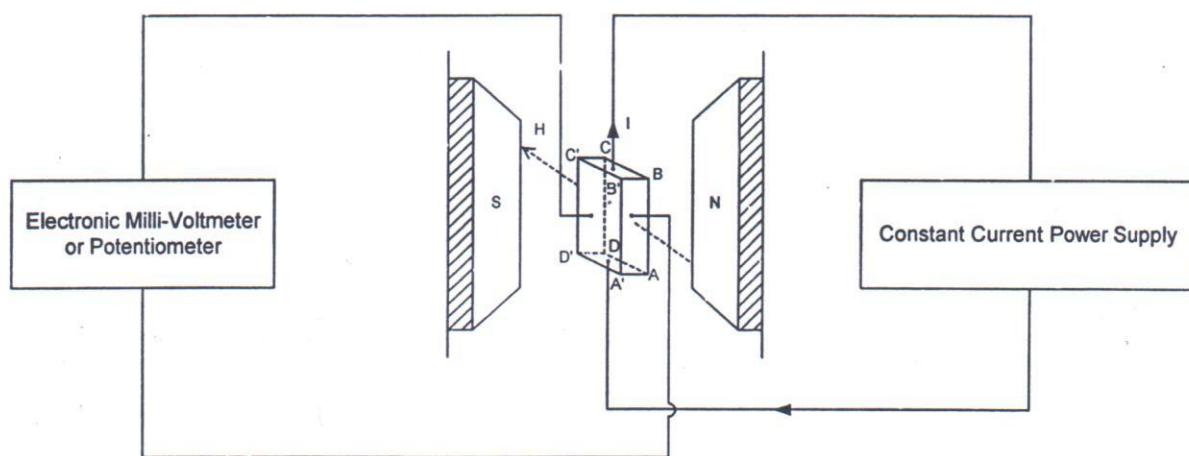


Fig. 3

INTRODUCTION

The conductivity measurements cannot reveal whether one or two types of carriers are present; nor distinguish between them. However, this information can be obtained from Hall Effect measurements, which are basic tools for the determination of mobilities. The effect was discovered by E.H. Hall in 1879.

THEORY

As you are undoubtedly aware, 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 (\vec{E}_h) which depends on the cross product of the magnetic intensity, \vec{H} , and the current density, \vec{J} . The situation is demonstrated in Fig. 1.

$$\vec{E}_h = R \vec{J} \times \vec{H}, \quad (1)$$

where R is called the Hall coefficient.

Now, let us consider a bar of semiconductor, having dimension, x , y and z . Let \vec{J} is directed along X and \vec{H} along Z then \vec{E}_h will be along Y , as in Fig. 2.

Then we could write

$$R = \frac{V_h/y}{JH} = \frac{V_h.z}{IH}, \quad (2)$$

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 if it is assumed that all carriers have the same drift velocity. We will do this in two steps (a) by assuming that carriers of only one type are present, and (b) by assuming that carriers of both types are present.

(a) One type of Carriers

Metals and degenerate (doped) semiconductors are the examples of this type where one carrier dominates.

The magnetic force on the carriers is $\vec{E}_m = e(\vec{v} \times \vec{H})$ and is compensated by the Hall field $\vec{F}_h = e\vec{E}_h$, where v is the drift velocity of the carriers. Assuming the direction of various vectors as before

$$\vec{v} \times \vec{H} = \vec{E}_h$$

From simple reasoning, the current density \vec{J} is the charge q multiplied by the number of carriers traversing per unit area in unit time, which is equivalent to the carrier density multiplied by the drift velocity i.e. $\vec{J} = q n \vec{v}$

By putting these values in equation (2)

$$R = \frac{E_h}{J H} = \frac{v \cdot H}{q n v H} = \frac{1}{n q} \quad (3)$$

From this equation, it is clear that the sign of Hall coefficient depend upon the sign of the q . This means, in a p-type specimen the R would be positive, while in n-type it would be negative. Also for a fixed magnetic field and input current, the Hall voltage is proportional to $1/n$ or its resistivity. When one carrier dominates, the conductivity of the material is $\sigma = n q \mu$, where μ is the mobility of the charge carriers. Thus $\mu = R \sigma$ (4)

Equation (4) provides an experimental measurement of mobility; R is expressed in $\text{cm}^3 \text{ coulomb}^{-1}$ thus μ is expressed in units, of $\text{cm}^2 \text{ volt}^{-1} \text{ sec}^{-1}$.

(b) Two type of Carriers

Intrinsic and lightly doped semiconductors are the examples of this type. In such cases, the quantitative interpretation of Hall coefficient is more difficult since both type of carriers contribute to the Hall field. It is also clear that for the same electric field, the Hall voltage of p-carriers will be opposite in sign to that from n-carriers. As a result, both mobilities enter into any calculation of Hall coefficient and a weighted average is the result* i.e.

$$R = \frac{\mu_h^2 p - \mu_e^2 n}{2(\mu_h p + \mu_e n)^2}, \quad (5)$$

where μ_h and μ_n are the mobilities of holes and electrons; p and n are the carrier densities of holes and electrons. Eq. (5) correctly reduces to equation (3) when only one type of carrier is present**.

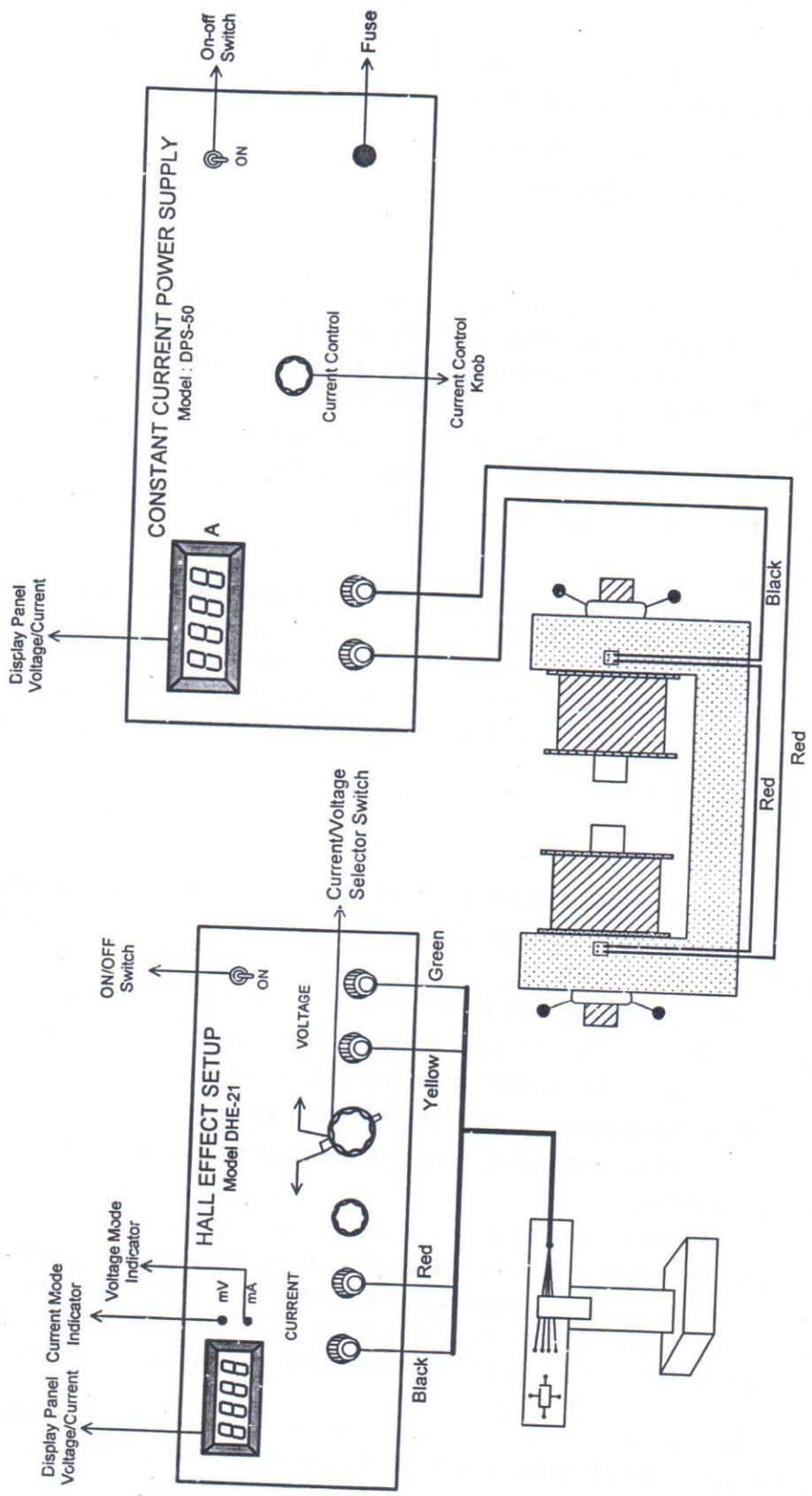
Since the mobilities μ_h and μ_n are not constants but function of temperature (T) the Hall coefficient given by Eq. (5), is also a function of T and it may become zero, even change sign. In general $\mu_n > \mu_h$ so that inversion may happen only if $p > n$; thus 'Hall coefficient inversion' is characteristic only of p-type semiconductors.

At the point of zero Hall coefficient, it is possible to determine the ratio of mobilities and their relative concentration.

Thus we see that the Hall coefficient, in conjunction with resistivity measurements, can provide information on carrier densities, mobilities, impurity concentration and other values. It must be noted, however, that mobilities obtained from Hall Effect measurements $\mu = R \sigma$ do not always agree with directly measured values. The reason being that carriers are distributed in energy, and those with higher velocities will be deviated to a greater extent for a given field.

* From Experiments in Modern Physics by Adrian C. Melissions (Academic Press) p. 86.

** Both Eq. (3) and Eq. (5) have been derived on the assumption that all carriers have same velocity; this is not true, but the exact calculation modifies the results obtained here by a factor of only $3\pi/8$.



Panel Diagram of Hall Effect Experiment, HEX-21

EXPERIMENTAL TECHNIQUE

(a) Experimental consideration relevant to all measurements on semiconductors

1. In single crystal material the resistivity may vary smoothly from point to point. In fact this is generally the case. The question is the amount of this variation rather than its presence. Often however, it's conventionally stated that it is a constant within some percentage and when the variation does in fact fall within this tolerance, it is ignored.
2. High resistance or rectification action appears fairly often in electrical contacts to semiconductors and in fact is one of the major problem.
3. Soldered probe contacts, though very much desirable may disturb the current flow (shorting out part of the sample). Soldering directly to the body of the sample can affect the sample properties due to heat and by contamination unless care is taken. These problems can be avoided by using pressure contacts as in the present set-up. The principal draw back of this type of contacts is that they may be noisy. This problem can, however, be managed by keeping the contacts clean and firm.
4. The current through the sample should not be large enough to cause heating. A further precaution is necessary to prevent 'injecting effect' from affecting the measurement. Even good contacts to germanium for example, may have this effect. This can be minimized by keeping the voltage drop at the contacts low. If the surface near the contacts is rough and the electric flow in the crystal is low, these injected carriers will recombine before reaching the measuring probes.
Since Hall coefficient is independent of current, it is possible to determine whether or not any of these effects are interfering by measuring the Hall coefficient at different values of current.

(b) Experimental consideration with the measurements of Hall Coefficient.

1. The voltage appearing between the Hall probes is not generally, the Hall voltage alone. There are other galvanomagnetic and thermomagnetic effects (Nernst effect, Rhighleduc effect and Ettingshausen effect) which can produce voltages between the Hall probes. In addition, IR drop due to probe misalignment (zero magnetic field potential) and thermoelectric voltage due to transverse thermal gradient may be present. All these except, the Ettingshausen effect are eliminated by the method of averaging four readings.

The Ettingshausen effect is negligible in materials in which a high thermal conductivity is primarily due to lattice conductivity or in which the thermoelectric power is small.

When the voltage between the Hall probes is measured for both directions of current, only the Hall voltage and IR drop reverse. Therefore, the average of these readings eliminates the influence of the other effects. Further, when Hall voltage is measured for both the directions of the magnetic field, the IR drop does not reverse and may therefore be eliminated.

2. The Hall probe must be rotated in the field until the position of maximum voltage is reached. This is the position when direction of current in the probe and magnetic field would be perpendicular to each other.
3. The resistance of the sample changes when the magnetic field is turned on. This phenomena called magneto-resistance is due to the fact that the drift velocity of all carriers is not the same, with 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 under compensated, resulting in trajectories that are not along the applied external field. This results in effective decrease of the mean free path and hence an increase in resistivity.

Therefore, while taking readings with a varying magnetic field at a particular current value, it is necessary that current value should be adjusted, every time. The problem can be eliminated by using a constant current power supply, which would keep the current constant irrespective of the resistance of the sample.

4. In general, the resistance of the sample is very high and the Hall voltages are very low. This means that practically there is hardly any current - not more than few micro amperes. Therefore, the Hall voltage should only be measured with a high input impedance ($\approx 1M$) devices such as electrometer, electronic millivoltmeters or good potentiometers preferably with lamp and scale arrangements.
5. Although the dimensions of the crystal do not appear in the formula except the thickness, but the theory assumes that all the carriers are moving only lengthwise. Practically it has been found that a closer to ideal situation may be obtained if the length may be taken three times the width of the crystal.

BRIEF DESCRIPTION OF THE APPARATUS

1. Hall Probe (Ge Crystal n & p type), HPN-21 & HPP-21 : One each
2. Hall Effect Set-up (Digital), DHE-21 : One
3. Electromagnet, Model EMU-75 or EMU-50V : One
4. Constant Current Power Supply, DPS-175 or DPS-50 : One
5. Digital Gaussmeter, DGM-102 : One

1. Hall Probe (Ge Crystal)

Ge single crystal with four spring type pressure contacts is mounted on a sunmica dedecorated bakelite strip. Four leads are provided for connections with measuring devices.

SPECIFICATIONS

Contacts	: Spring type (Solid Silver)
Hall Voltage	: 0.1 - 1 Volt/100 mA/KG
Thickness of Ge Crystal	: 0.4 - 0.5 m.m.
Resistivity	: $\approx 10 \Omega \text{ cm.}$

The exact value of thickness and resistivity is provided in the test report of the Hall Probe (Ge) supplied with the set-up. The student after calculating the Hall Coefficient from this experiment and using the given value of resistivity can also get valuable information about **carrier density and carrier mobilities**. A typical example is provided in the appendix. A further advantage of this type of probe is that the sample can be changed. A minor draw back of this arrangement is that the it may require zero adjustment from time to time. This type of probes are specially designed and recommended for Hall Effect experiment.

2. Hall Effect Set-up (Digital), DHE-21

It is a high performance instrument of outstanding flexibility. The set-up consists of an electronic digital millivoltmeter and a constant current power supply. The Hall Voltage and probe current can be read on the same digital panel meter through the selector switch.

(a) Digital Millivoltmeter

Intersil 3½ digit single chip A/D Converter ICL 7107 have been used. It has high accuracy like, auto zero to less than 10 μV , zero drift less than $1 \mu\text{V}/^\circ\text{C}$, input bias current of 10 pA and roll over error of less than one count. Since the use of internal reference causes the degradation in performance due to internal heating, an external reference has been used. This voltmeter is much more convenient to use in Hall experiment, because the input of either polarity can be measured.

SPECIFICATIONS

Range	: 0 - 200.0 mV
Resolution	: 100 μV
Accuracy	: $\pm 0.1\%$ of reading ± 1 digit
Impedance	: 1 ohm
Special Features	: Auto Zero & polarity indicator
Overload Indicator	: Sign of 1 on the left & blanking of other digits.

(b) Constant Current Generator

This power supply specially designed for Hall Probe provides 100 percent protection against crystal burn-out due to excessive current. The basic scheme is to use the feed - back principle to limit the load current of the supply to a pre - set maximum value. Variations in the current are achieved by a potentiometer. The supply is a highly regulated and practically ripple free d.c. source. The current is measured by the digital panel meter.

SPECIFICATIONS

Current Range	: (0 - 20 mA) or as required for the particular Hall Probe
Resolution	: 10 μA
Accuracy	: $\pm 0.2\%$ of the reading ± 1 digit
Load regulation	: 0.03% for 0 to full load
Line regulation	: 0.05% for 10% changes.

3. (a) Electromagnet, EMU-75

Field intensity	: $11,000 \pm 5\%$ gauss 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

(b) Electromagnet, EMU-50V

Field intensity	: 7.5 K gauss at 10 mm. The air-gap is continuously variable with two way knobbed wheel screw adjusting system.
Pole pieces	: 50 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 about 3.0 ohm
Yoke material	: 'U' shaped soft iron
Power requirement	: 0 - 30 V @ 4.0 A, if coils are connected in series.

4. (a) 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. All the six constant current sources are individually IC controlled and hence result in the highest quality of performance. The supply is protected against transients caused by the load inductance.

SPECIFICATIONS

Current	: Smoothly adjustable from 0 to 3.5 A. per coil, i.e. 7A
Regulation (line)	: $\pm 0.1\%$ for 10% mains variation.
Regulation (load)	: $+ 0.1\%$ for load resistance variation from 0 to full load
Open circuit voltage	: 50 volt
Metering	: 3½ digit, 7 segment panel meter.

(b) Constant Current Power Supply, DPS-50

The present constant current source is an inexpensive and high performance unit suitable for small and medium sized electromagnets. Although the equipment was designed for the electromagnet, model EMU-50, it can be used satisfactorily with any other electromagnet provided the coil resistance does not exceed 6 ohm.

The current regulation circuit is IC controlled and hence result in the highest quality of performance. Matched power transistors are used to share the load current. The supply is protected against transients caused by the inductive load of the magnet.

SPECIFICATIONS

Current range	: 0 - 4 A (or as desired)
Load regulation	: 0.1% for load resistance variation from zero to maximum
Line regulation	: 0.1% for $\pm 10\%$ mains variation
Protected	: Electronically protected against overload or short circuit
Display	: 3½ digit, 7 segment LCD DPM

5. 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. This small Hall Voltage is amplified through a high stability amplifier so that a millivoltmeter connected at the output of the amplifier can be calibrated directly in magnetic field unit (gauss).

SPECIFICATIONS

Range	: 0 - 2 K gauss & 0 - 20 K gauss
Resolution	: 1 gauss at 0 - 2 K gauss range
Accuracy	: $\pm 0.5\%$
Display	: 3½ digit, 7 segment LED
Detector	: Hall probe with an Imported Hall Element
Power	: 220V, 50 Hz
Special	: Indicates the direction of the magnetic field.

PROCEDURE

1. Note the ambient temperature.
2. Connect the widthwise contacts of the Hall Probe to the terminals marked 'Voltage' and lengthwise contacts to terminals marked 'Current'.
Red + / Black - Yellow + / Green -
3. Switch 'ON' the Hall Effect set-up and adjustment current (say few mA).
4. Switch over the display to voltage side. There may be some voltage reading even outside the magnetic field. This is due to imperfect alignment of the four contacts of the Hall Probe and is generally known as the 'Zero Field Potential'. In case its value is comparable to the Hall Voltage it should be adjusted to a minimum possible (for Hall Probe (Ge) only). In all cases, this error should be subtracted from the Hall Voltage reading.
5. Now place the probe in the magnetic field as shown in fig. 3 and switch on the electromagnet power supply and adjust the current to any desired value. Rotate the Hall probe till it become perpendicular to magnetic field. Hall voltage will be maximum in this adjustment.
6. Measure Hall voltage for both the directions of the current and magnetic field (i.e. four observations for a particular value of current and magnetic field).
7. Measure the Hall voltage as a function of magnetic field keeping a suitable value of current as constant. Plot graph.
8. Measure the magnetic field by the Gaussmeter.

CALCULATIONS

- (a) From the graph Hall voltage Vs. magnetic field calculate Hall coefficient.
- (b) Determine the type of majority charge carriers, i.e. whether the crystal is n type or p type.
- (c) Calculate charge carrier density from the relation
$$R = \frac{1}{nq} \Rightarrow n = \frac{1}{Rq}$$
- (d) Calculate carrier mobility, using, the formula
$$\mu_n \text{ (or } \mu_p) = R\sigma$$

using the specified value of resistivity ($1/\sigma$) given by the supplier or obtained by some other method (Four Probe Method). *Typical calculations are shown in appendix*

QUESTIONS

1. What is Hall Effect?
2. What are n-type and p-type semiconductors?
3. What is the effect of temperature on Hall coefficient of a lightly doped semiconductor?
4. Do the holes actually move ?
5. Why the resistance of the sample increases with the increase of magnetic field?
6. Why a high input impedance device is generally needed to measure the Hall voltage?
7. Why the Hall voltage should be measured for both the directions of current as well as of magnetic field?

REFERENCES FOR SUPPLEMENTARY READING

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3. Experiments in Modern Physics, A.C. Melissios, Academic Press, N.Y. (1966).
4. Electrons and Holes, W. Shockley, D. Van Nostrand ,N.Y. (1950).
5. Hall Effect and Related Phenomena, E.H. Putley, Butterworths, London (1960).
6. Handbook of Semiconductor Electronics, L.P. Hunter (e.d.) McGraw Hill Book Co. Inc., N.Y. (1962).

APPENDIX

Sample calculation for Hall Coefficient, Carrier Density and Mobility taking Hall Probe S.No. 500 as sample.

Sample Details

Sample	: Ge crystal n- type	$\left. \begin{aligned} \text{ohm} &= \frac{V}{I} = \frac{V}{\frac{dQ}{dt}} = V \cdot \text{coulomb}^{-1} \cdot \text{sec} \\ & \end{aligned} \right\}$
Thickness (z)	: 5×10^{-2} cm.	
Resistivity (ρ)	: 10 ohm. cm. or $10 \text{ volt coulomb}^{-1} \text{ sec cm}$	
Conductivity (σ)	: $0.1 \text{ coulomb volt}^{-1} \text{ sec}^{-1} \text{ cm}^{-1}$	

Experimental Data

Current (I)	: 8×10^{-3} A
Magnetic Field (H)	: 1000 G
Hall Voltage (V_h)	: 53×10^{-3} V

(i) Hall Coefficient (R)

We know from equation 2 of the text

$$\begin{aligned}
 R &= \frac{V_h \cdot z}{I H} \\
 &= \frac{53 \times 10^{-3} \times 5 \times 10^{-2}}{8 \times 10^{-3} \times 10^3} \\
 &= 33 \times 10^{-5} \text{ volt cm amp}^{-1} \text{ G}^{-1} \\
 \text{or} &= 33 \times 10^{-5} \times 10^8 \text{ cm}^3 \text{ coulomb} \\
 &= 33 \times 10^3 \text{ cm}^3 \text{ coulomb}^{-1}
 \end{aligned}$$

(ii) Carrier Density (n)

We know from equation 3 of the text

$$\begin{aligned}
 R &= \frac{1}{nq} \Rightarrow n = \frac{1}{Rq} \\
 &= \frac{1}{33 \times 10^3 \times 1.6 \times 10^{-19}} \\
 &= 1.9 \times 10^{14} \text{ cm}^{-3}
 \end{aligned}$$

(iii) Carrier Mobility

For degenerate semiconductor i.e. when one carrier dominates.

$$\begin{aligned}
 \text{Carrier Mobility} \quad \mu &= R\sigma \\
 &= 33 \times 10^{-5} \times 0.1 \\
 &= 3300 \text{ cm}^2 \text{ volt}^{-1} \text{ sec}^{-1}
 \end{aligned}$$

Thus we see that Hall Coefficient in conjunction with resistivity measurement can provide valuable information on carrier density, mobilities and other values. It must be noted however, that mobilities obtained from Hall Effect measurement $\mu=R\sigma$ do not always agree with directly measured values. The reason is explained in the booklet.