THE PROPERTIES OF
PAKISTANI SEMI-CONDUCTING ORES

A

THESIS

SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING, EPUET, DACCA, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ELECTRICAL ENGINEERING.

BY

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JUNE, 1965.

CERTIFICATE

THIS IS TO CERTIFY THAT THIS WORK WAS DONE BY ME AND IT HAS NOT BEEN SUBMITTED ELSEWHERE FOR THE AWARD OF ANY OTHER DEGREE OR DIPLOMA.

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THE AUTHOR.

ABSTRACT

Hall effect which gives very useful information about semi-conductors has been investigated for different semi-conducting ores available in Pakistan in the present work. The other properties such as Hall co-efficient, resistivity, type of semi-conductors, majority and minority carrier concentration, intrinsic carrier concentration, mobility, energy gap, magneto-resistance, diffusion co-efficient, number of atoms per cubic meter etc. have also been investigated for some promising semi-conducting ores such as Pyrite, Leadsulphide, Stinbite, etc. The experiments on the samples of Pyrite and Leadsulphide have been carried out on the assumption of their extrinsic and intrinsic nature while that on the sample of Stibnite on the assumption of its extrinsic nature only. The results obtained have been discussed and compared with those obtained by other workers.

A summary of the results obtained has been tabulated at the end of the text. The values of Germanium shown in the table have not been determined and supplied only for the convenience of comparison.

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NOMENCULTURE

The following nomenculture defines the symbols used generally throughout the text.

a = Lattice Constant in A^o

A = Ampere; cross sectional area

B = Battery; Magnetic field intensity in Web/ m^2

c = Axial lattice constant in A^o . ; ratio of mobilities $\left(\frac{\mu_e}{\mu_h}\right)$

C = Coulomb

D = Diffusion constant in m^2/Sec.

e = Electronic charge in coulomb

ev = Electron volt

$E_x E_y$ = Electric field in V/m in the direction x, y

F_y = Lorentz force in the direction y

fcc = Face centred cubic

$F_e S_2$ = Pyrite (Iron Sulphide)

H = Magnetic field intensity

I = Current in ampere

I_{ee} = Electron current in the emitter circuit

I_{ec} = Electron current in the collector circuit

I_{eh} = Hole current in the emitter circuit

J = Current density in ampere/ m^2

R = Boltzman's constant.

l = Length

L = Diffusion length in meter

m = Mass of an electron; meter

m_e, m_h = Effective mass of electrons and holes

mA = Milliamp

mV = Millivolt

μ_e = Electron mobility in meter/ V-sec.

μ_h = Hole mobility in meter/ V-sec.

μ_r = Relative permeability

n = Integers; carrier concentration in general

n_i = Intrinsic carrier concentration in cubic meter

n_e = Density of electrons in a conduction band

n_e, n_h = Concentration of electrons and holes respectively

n_v = Density of electrons in valence band

N = Number of atoms/ unit vol.

θ_H = Hall angle

PbS = Leadsulphide

R = Resistance in ohm

R_H = Hall co-efficient in m^3/C

ρ = Resistivity in ohm-meter in presence of magnetic field

ρ_0 = Resistivity in the absence of magnetic field

$\Delta\rho$ = Change of resistivity

ρ_m = Magneto-resistance in percent

Sb_2S_3 = Stibnite (Antimony sulphide)

τ = Relaxation time

T = Temperature in degree kelvin

V_x = Velocity of electron in the direction x

V = Volt

V_H = Hall voltage in millivolt

W = Energy in general in electron volt

W_c = Energy corresponding to the bottom of the conduction band

W_g = Energy corresponding to the forbidden band

W_F = Energy corresponding to the Fermi-level

Web./m^2 = Weber per square meter

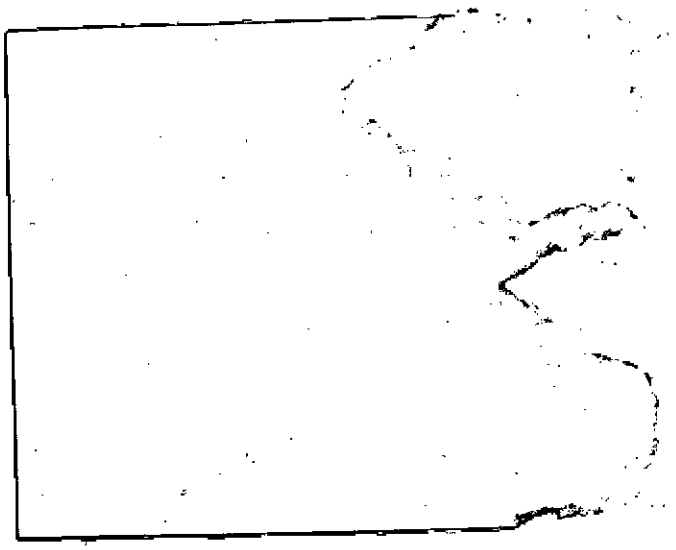
Z = Number of atoms/ m^3

σ = Conductivity in mho/ m

Ω = ohm

+, O = Holes

−, • = Electrons



THE ELECTRO MAGNET

&

THE SAMPLE HOLDER

PHOTOGRAPH - 1

CHAPTER - 1

INTRODUCTION

1.1 INTRODUCTION

The study of the properties of indigenous semi-conducting ores available in Pakistan were undertaken at the Electronics Laboratory of the Engineering University and the present work is a continuation of the previous work.

The diode and triode action of Pakistani semi-conductors had been carried out in an earlier work by the author[1]. An encouraging diode action of some materials was obtained while little or no triode action was obtained. Controlled atmospheric condition, which is an essential factor for obtaining good triode action, was not available. However, the possibility of using the ores as detectors of radio signals was carried out and hopeful results were obtained.

The present work covers Hall effect which gives very useful information about semi-conductors. The other properties such as carrier concentration, type of semi-conductors from Hall co-efficient, Hall angle, mobility, intrinsic carrier concentration, energy gap, magneto-resistance etc. have also been investigated for some promising materials such as Leadsulphide, Stibnite, Pyrite etc. The results obtained have been discussed and compared with those obtained by other workers.

Hall effect was discovered as early as in 1879. Since then much work has been done on the subject by a large number of scientists and it is needless to say that the study is not yet exhaustive, specially for semi-conducting ores available in Pakistan.

A great interest was seen in this direction only very recently in 1948, when semi-conductors entered the field of practical science. With the ever growing importance of semi-conductors in the practical field, great efforts are being made to find out the semi-conducting properties of different materials for utilising them in newer branches of technology.

1.2 LITERATURE SURVEY AND THE PRESENT POSITION

As the present work is concerned with the properties of semi-conducting ores, the author desires to recall the most important works done in the field so far. In 1879, E.H. Hall[2,3] discovered the action of magnetic field on a permanent electric current. Lorentz has proved that the force F exerted on an electron by a combined electric field E and magnetic field B is given by

$$F = -e \left[E + v \times B \right]$$

The free electrons are driven towards the faces of a semi-conducting sample, resulting in excess of charge carriers on the faces. This in turn creates Hall voltage.

Hall observed this action first in gold. He latter studied this effect

on iron, silver, and tin. Before him, two other scientists Feitzsch in 1858 and Mach in 1870 and Rowland carried out similar investigation but obtained no result.

A.H. Wilson[4] (1931) explained this effect from the view point of electron theory. In 1933, Fowler[5] studied the Hall effect theoretically to account for the observed positive, zero and negative Hall co-efficients.

In 1935, I.H. Hall observed the Ettingshausen effect, the Nernst effect and the Leduc effect in excess to Hall effect in copper at various temperatures ranging from 20°C to 90°C.

E. Conwell and V.E. Weisskopf measured the Hall co-efficients and resistivity of Germanium semi-conductors in 1946 and found that simple theory of lattice scattering alone could not explain the temperature dependence of mobilities. Another source of resistance was scattering by impurity centre such as Rutherford scattering of electrons or holes by a random distribution of impurity ions.

In 1949, G.L. Pearson and J. Bardeen[6] made a theoretical and experimental study of the electrical resistivity and of Hall co-efficients of pure silicon and silicon alloys containing Boron (p - type impurity) and phosphorous (n - type impurity) over a range of temperature from 87°K to 900°K. The temperature variations of the concentration of carriers and their mobilities were determined from the resistivity and the Hall data for different samples.

Hall co-efficient and conductivity of lead sulphide were made at room temperature by Dr. E.H. Putely and Mr. J.B. Arther[7] in 1951. Their work indicated that the sample might be a p - type or n - type semi-conductor with

carrier concentration ranging from 10^{21} to 10^{26} / m^3 of either sign. It was also found that by suitable heat treatments p-type specimen might be converted to n-type and vice-versa. The same experiment was done by Dunaev and Maslakovitz[8] in 1947. They measured the conductivity and Hall co-efficient upto a temperature of 900°K but did not find any evidence for intrinsic conductivity. Their samples were rather impure. They found out the energy gap of the order of 0.37 ev. But Putely and Arther performed experiments with comparatively pure samples, which showed intrinsic conductivity. Thus they inferred that lead sulphide exhibited intrinsic conductivity, and behaved quantitatively according to the accepted semi-conductor model with an energy gap of about 0.3 to 1.2 ev.

Measurement on the electrical properties of PbS and other semi-conductors was also carried out by Sisenmann[9], Hintenberger[10], Morton[11], Chasmer[12], Michelssen[13], Gentav[14], Scanlon[15], Putely,[16] Banbury[17], Moss[18], Scanlon[19] and many other workers.

There does not seem to be much work done on this subject in our country in the past. Some students[20] of Dacca University in the recent past concentrated mostly their work on sintered samples of Pakistani origin and the only one natural ore on which work was carried out, happened to be Stibnite (Sb_2S_3). Values of Hall co-efficients, nature of carriers, carrier concentration, mobilities and magneto-resistance for the specimen were obtained.

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CHAPTER - 2

PAKISTANI SEMI-CONDUCTING ORES

2.1 PAKISTANI SEMI-CONDUCTING ORES

There are many semi-conducting ores available in Pakistan. Of these, Pyrite , Gallena, Stibnite, Graphite, Sulphur, Bauxite, Magnetite, Limonite, Hematite, Halite, Arsenic, Potash salt and Manganese ore most important.

Of the above, the first three i.e. Pyrite, Gallena and Stibnite are the most promising semi-conductors and therefore chosen for investigation.

Pyrite, an ore of Iron & Sulphur, occurs in Chandranath Hill of Chittagong district and Matamuhuri Reserve Forest Area of Chittagong Hill Tracts.

Gallena , an ore of Lead and Sulphur, is available in West Pakistan.

Stibnite, an ore of Autimony and Sulphur, occurs also in West Pakistan.

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CHAPTER - 3

THEORETICAL CONSIDERATIONS

3.1 SEMI- CONDUCTORS

Semi-conductors[21] are electronic conductors with values of electrical resistivity at room temperature generally in the range of 10^{-2} - 10^{9} ohm-cm. intermediate between good conductors (10^{-5} ohm-cm) and insulators (10^{14} - 10^{22} ohm-cm).

At absolute zero, a pure and perfect crystal of most semi-conductors would behave as an insulator. The characteristics of semi-conducting properties are brought about by thermal agitation, impurities or lattice defect.

3.2 DISTINCTION BETWEEN METAL, SEMI-CONDUCTOR AND INSULATOR

METAL	SEMI-CONDUCTOR	INSULATOR
1. A large number of free electrons at 0°K.	No free electrons at 0°K.	No free electrons at 0°K.
2. Large number of free electrons at room temperature (300°K.)	Few free electrons at 300 °K.	Very small number of free electrons at 300 °K.
3. No energy gap.	Small energy gap.	Large energy gap.
4. Positive temperature co-efficient.	Negative temperature co-efficient.	Negative temperature co-efficient.
5. n_i = constant.	$n_i = 5 \times 10^{21} T^{3/2} e^{-W_g/2kT}/m^3$	$n_i = 5 \times 10^{21} T^{3/2} e^{-W_g/2kT}/m^3$

3.3 METHOD OF CRYSTAL ANALYSIS

Crystals are usually analysed by X-ray diffraction. The edge of unit cube is determined by Bragg's diffraction formula, $a = \frac{n\lambda}{2 \sin\theta}$ .....(1)

where λ = wavelength of x-ray

θ = angle between the x-ray beam and the atomic planes.

n = integers, 1,2,3, etc.

The above method also provides us with the knowledge of arrangement of atoms in the crystal.

3.4 CRYSTAL STRUCTURES OF SELECTED ORES

Crystal	Structure	Lattice constants at room temperature a(in A°)	C (axial)	Atoms/unit cell	Individual Structure
PbS	fcc (Same as Nacl)	5.92 A		$4+4 = 8^{\frac{22}{}}$	Pb=fcc = 4 S=fcc = 4
FeS_2	Complex cubic	5.407 A		$4+4 = 8^{\frac{23}{}}$	$2Fe$=bcc = 4 S =fcc = 4
Sb_2S_3	Cubic (same as ZnS)	6.0 A (Assuming)		$4+4 = 8^{\frac{24}{}}$	Sb =fcc = 4 (assumed) S =fcc = 4
Nacl	fcc	5.63		$4+4 = 8^{\frac{22}{}}$	Na =fcc = 4 cl =fcc = 4
Graphite (C+ Pb)	Hexagonal h cp (cp= closed packed)	2.4611	6.707	$2+2 = 4^{\frac{25}{}}$	Graphite = hcp = 2

3.5 HALL EFFECT

Hall effect gives some very important information on semi-conductors. Essentially it is the potential drop that appears across two opposite faces of a semi-conductor slab, provided a strong magnetic field and a current flow through the slab, perpendicular to the direction of appearance of voltage is allowed.

A. Consider a slab[26] of p-type material in which there is a current density J resulting from an applied electric field E_x. Since the carriers are assumed to be positive, they will drift with an average velocity $\langle V_x \rangle$ in the x direction.

The force exerted on a hole of charge e by a combined electric and magnetic field is given by Larents formula

$$F = e\left[E + V \times B\right] \quad \ldots\ldots \quad (2)$$

Under condition of equilibrium, Fy = 0

$$\therefore \quad E_y + V_x \times B_z = 0$$

$$\text{or} \quad E_y = -V_x \times B_z = V_x B_z \quad \ldots\ldots(i)$$

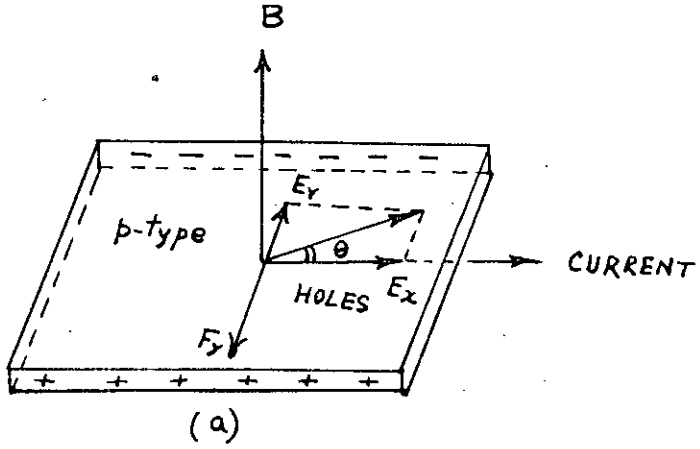
On the other hand, the current density in the sample is given by

$$J_x = n_h e \langle V_x \rangle \quad \ldots\ldots(ii)$$

Eliminating V_x from the equations (i),(ii) we may define the Hall coefficient R_H as

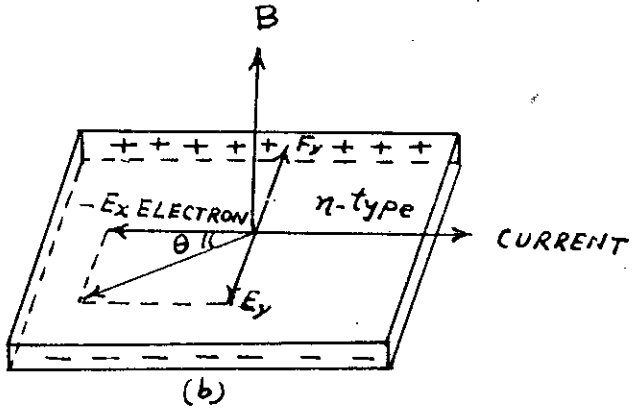
$$R_H = \frac{E_y}{B_z J_x} = \frac{V_x}{n_h e V_x} = \frac{1}{n_h e} \quad \ldots\ldots\ldots\ldots(3)$$

The current density J_x can be calculated from the total current and the cross section of the sample. The field E_y may be found by attaching voltage probes



(a)

POSITIVE HALL EFFECT



(b)

NEGATIVE HALL EFFECT

Fig. 1.

at the front and back faces of the sample and by dividing the measured Hall voltage by the width of the sample in the y direction. Thus R_H can be obtained from measurements and n_h can be calculated. It should be noted here that proper averaging over the velocity distribution of the carriers gives $R_H = \frac{A}{e\, n_h}$, where A is a constant of the order of unity. For a simple semi-conductor model,[27]

$$R_H = \frac{1}{n_h e} \frac{\langle v^2 \tau^2 \rangle v^2}{(v^2 \tau)^2} \qquad \ldots\ldots\ldots\ldots \quad (4)$$

$\tau = \frac{\lambda}{v}$ where λ = mean free path

v = velocity of electrons.

If mean free path is dependent on velocity v^p, then the expression[28]

$$\frac{\langle v^2 \tau^2 \rangle (v)^2}{(v^2 \tau)^2} = \frac{3\pi^{\frac{1}{2}} \Gamma(p+3/2)}{4 \left\{\Gamma(p/2+2)\right\}^2}$$

1) For lattice scattering, λ is independent of velocity

i.e. $p = 0$ the expression $= \frac{3\pi^{\frac{1}{2}} \Gamma 3/2}{4(\Gamma 2)^2} = \frac{3\pi}{8}$

Hence $R_H = \frac{3\pi}{8} \frac{1}{n_h e} \qquad \ldots\ldots\ldots\ldots (5)$

2) For impurity scattering, $p \simeq 4$, the expression ~ 1.93

when $R_H = 1.93 \frac{1}{n_h e} \qquad \ldots\ldots\ldots\ldots (6)$

An intermediate value is used when both lattice and impurity scattering are present. For simple lattice scattering, the factor $3\pi/8$ has been used throughout the present work.

B. If the carriers were electrons instead of holes, the polarity of V_H would be reversed.

Hence $$R_H = \frac{E_y}{B_z J_x} = - \frac{1}{e\, n_e} \quad \ldots\ldots\ldots\ldots \quad (7)$$

where n_e = density of conduction electrons.

We thus conclude that a measurement of Hall co-efficient of a semi-conductor with one kind of charge carriers provides us with:

a) the sign of charge carriers

b) the density of charge carriers.

HALL ANGLE : It is defined by θ_H as

$$\theta_H = \tan \theta_H = \frac{E_y}{E_x} = R_H B_z \sigma \quad \ldots\ldots\ldots(8)$$

Since $$R_H = \frac{E_y}{B_z \sigma E_x} .$$

3.6 CARRIER CONCENTRATION : Since R_H for lattice scattering is given by

$R_H = \pm \frac{3\pi}{8} \frac{1}{n e}$ where + sign stands for holes and
- sign stands for electrons.

Hence $$n = \pm \frac{3\pi}{8 e} \frac{1}{R_H} \quad \ldots\ldots\ldots\ldots \quad (9)$$

So from a measurement of Hall co-efficient carrier concentration can be calculated.

MOBILITY : It is the drift velocity attained by an electron per unit electric field and is given by

$$\sigma = \pm\, ne\mu \text{ (for one type of charge carriers)}$$

when $$\mu = \pm \frac{\sigma}{n e} = \pm \frac{\sigma}{\frac{3\pi}{8} R_H} = \pm (8/3\pi)\, \sigma\, R_H \quad \ldots\ldots(10)$$

The above theory is applicable in case of one type of charge carriers.

3.7 INTRINSIC SEMI-CONDUCTORS

When two types of carriers are present,

a) the conductivity of semi-conductors may be expressed by[29]

$$\sigma = \frac{n_e e^2 \tau_e}{m_e} + \frac{n_h e^2 \tau_h}{m_h}$$

$$= n_e e \mu_e + n_h e \mu_h \quad \ldots\ldots\ldots\ldots \quad (11)$$

where n_e = conduction electrons/ m^3

n_h = conduction holes / m^3

μ_e, μ_h = drift mobilities for electrons and holes respectively.

e = electronic charge

b) Hall co-efficient, may be expressed by

$$R_H = \frac{E_y}{B_z J_x} = \frac{3\pi}{8e} \cdot \frac{n_h^2 \mu_h^2 - n_e^2 \mu_e^2}{(n_h \mu_h + n_e \mu_e)^2} \quad \ldots\ldots (12)$$

The result may be obtained in the following way :

When both types of charge carriers are present,

$$\sigma = e(n_e \mu_e + n_h \mu_h)$$

The force exerted on a hole of charge e by a combined electric and magnetic field is given by $F = e(E + v \times B)$

Under condition of equillibrium, $F_y = 0$

Therefore $E_y + v_x \times B_z = 0$

or $E_y - v_x B_z = 0$

or $E_y = v_x B_x$

Now (v_x), drift velocity of holes $= \frac{e \tau_h E}{m_h} = \mu_h E$

(v_x), drift velocity of electrons $= -\frac{e \tau_e E}{m_e} = -\mu_e E$

or V_x for both electrons and holes $= (\mu_h - \mu_e) E$.

or $E_y = (\mu_h - \mu_e) E B_z$. [since $E_Y = v_x B_z$].

$$= (\mu_h - \mu_e) B_z \frac{J_x}{e (n_e \mu_e + n_h \mu_h)}$$

Therefore, $R_H = \frac{E_y}{B_z J_x} = \frac{\mu_h - \mu_e}{e (n_e \mu_e + n_h \mu_h)}$

$$= \frac{1}{e} \frac{n_h \mu_h^2 - n_e \mu_e^2 + \mu_e \mu_h (n_e - n_h)}{(n_e \mu_e + n_h \mu_h)^2}$$

since $n_e = n_h = n_i$

or $n_e - n_h = 0$

or $R_H = \frac{n_h \mu_h^2 - n_e \mu_e^2}{e (n_e \mu_e + n_h \mu_h)^2}$ ..... (12)

$$= \frac{(n_h - n_e c^2)}{(n_h + n_e c)^2} \quad \text{..... (12a)}$$

where $c = \frac{\mu_e}{\mu_h}$

and $\sigma = e (n_e \mu_e + n_h \mu_h)$

$$= e n_h \mu_h \left(\frac{n_e}{n_h} c + 1 \right) \text{ ..... (11a)}$$

i) IDEAL INTRINSIC CASE

If $n_e = n_h = n_i$, we have ,

$$\sigma = n_i e (\mu_e + \mu_h) = n_i e \mu_h (c + 1) \quad \ldots\ldots\ldots (13)$$

$$R_H = \frac{3\pi}{8e} \frac{n_i (1 - c^2)}{n_i^2 (1 + c)^2}$$

$$= \frac{3\pi}{8 e n_i} \frac{1-c}{1+c} \quad \ldots\ldots\ldots\ldots\ldots (14)$$

Hence concentration is given by

$$n_i = \frac{3\pi}{8 e R_H} \frac{1 - c}{1 + c} \quad \ldots\ldots\ldots\ldots\ldots (15)$$

Apparant mobility is given by

$$= \frac{8}{3\pi} R_H \sigma$$

$$= \frac{8}{3\pi} \left(\frac{3\pi}{8 e n_i} \frac{1 - c}{1 + c} \right) \times n_i e \mu_h (c + 1)$$

or $$\mu = (1 - c) \mu_h \quad \ldots\ldots\ldots\ldots (16)$$

The mobility [30] relating with mean free path and effective mass m is also given by

$$\mu = \frac{4}{3} e \lambda (2\pi m_e kT)^{-\frac{1}{2}} \quad \ldots\ldots\ldots (17)$$

If $m_e = m$, the mass of an electron in free space,

$$= 2.43 \times 10^{15} \lambda T^{-\frac{1}{2}} \quad \ldots\ldots\ldots\ldots (18)$$

$$\lambda = 4.1 \times 10^{-16} \mu T^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots \quad (19)$$

The equations(17), (18), (19) may be applied to either electron or hole mobility, provided that the proper effective mass is used.

ii) NON-IDEAL INTRINSIC CASE

Let n_s = the saturation concentration

$$n_s = n_e - n_h \text{ (n - type)}$$

$$n_s = n_h - n_e \text{ (p-type)}$$

Hence conductity may be expressed in the form

$$\sigma = e \mu h (c n_e + n_h) \ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

For a p - type sample, $n_e = n_h - n_s$, we have

$$\sigma = e \mu h (c n_h - c n_s + n_h)$$

or $$n_h = (\sigma / e \mu h + c n_s) / (c + 1) \quad \ldots\ldots\ldots (21)$$

For a n -type sample , $n_e = n_h + n_s$

$$n_h = (\sigma / e \mu h - c n_s) / (c + 1) \quad \ldots\ldots\ldots (22)$$

3.8 INTRINSIC CARRIER DENSITIES AND ENERGY GAP FROM MODEL

I A simplified model[31] of a semi-conductor or insulator :

At absolute zero temperature, all semi-conductors are insulators as all the energy levels are completely filled, and the conduction band at T= 0 is completely empty.

At temperatures higher than zero, the density of electrons in a conduction band is given by,

$$n_c = \frac{Z}{e^{(W_c - W_F)/kT} + 1} \qquad \text{.....(i)}$$

where Z = number of possible states/unit volume.

Similarly, the density of electrons in the valence band is,

$$n_v = \frac{Z}{e^{\frac{-W_F}{kT}} + 1} \qquad \text{.....(ii)}$$

Again, neglecting spin, $n_c + n_v = Z$ ..... (iii)

From (i),(ii) and (iii) we have ,

$$W_F = \frac{W_c}{2} = \frac{W_g}{2} \qquad \text{.....(23)}$$

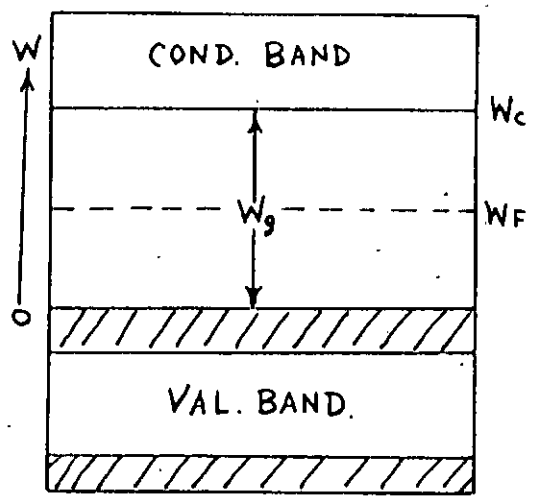
Hence Fermi Energy lies half way between the top of valence band and bottom of conduction band.

Again $$n_c = \frac{Z}{e^{(W_c - W_F)/kT} + 1} = \frac{Z}{e^{W_g/2kT} + 1}$$

$$= \frac{Z}{e^{W_g/2kT}} \quad \text{Since } W_g \text{ is large greater than } 2kT.$$

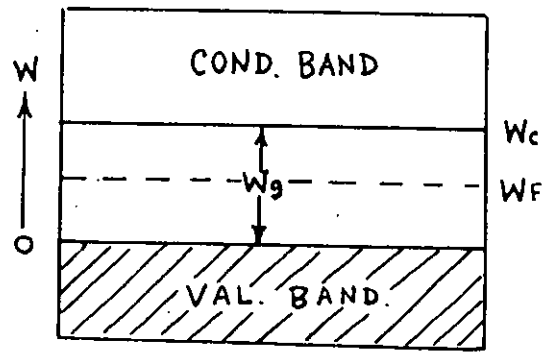
$$n_c = Z\, e^{-W_g/2kT} = 10^{28} e^{-W_g/2kT} \text{ per meter cube.....(24)}$$

where Z is assumed to be 10^{28}.



(a)

INSULATOR WITH FERMI LEVEL HALF WAY BETWEEN VALENCE AND CONDUCTION BAND.



(b)

ENERGY BANDS IN SEMI-CONDUCTORS

Fig. 2.

II Improved model for intrinsic semi-conductor.

When the width of the allowed energy bands becomes comparable with the width of the forbidden region, the density of conduction electrons is given by ,

$$n_e = \int_{W_g}^{top} Z(W)\, F(W)\, dW.$$

Now the number of states per unit volume

$$Z(W)dW = (4\pi)\,(2\, m_e^*/h^2)^{3/2}(W - W_g)^{\frac{1}{2}}\, dW \quad 32$$

Now $F(W) = \dfrac{1}{e^{(W-W_F)/kT} + 1} = e^{(W_F - W)/kT}$

Since $(W - W_F)$ is large greater than kT at low temperature.

$$n_e = \int_{W_g}^{\infty} Z(W)\, F(W)\, dW$$

$$= 4\pi(2\, m_e^*/h^2)^{3/2}\, e^{W_F/kT} \int_{W_g}^{\infty} (W - W_g)^{\frac{1}{2}}\, e^{-W/kT}\, dW$$

$$= 4\pi(2\, m_e^*/h^2)^{3/2}\, e^{(W_F - W_g)/kT} \cdot \frac{\pi^{\frac{1}{2}}}{2\,(1/kT)^{3/2}}$$

$$\text{or } n_e = 2\left(\frac{2\pi m_e^{*}\, kT}{h^2}\right)^{3/2} e^{(W_F - W_g)/kT} \quad \ldots\ldots\ldots (25)$$

Similarly, density of holes in the valence band may be written as

$$n_h = \int_{-\infty}^{0} Z(W)\, F(W)\, dW$$

Now, $Z(W)\, dW = 4\pi(2\, m_h^*/h^2)^{3/2}(-W)^{\frac{1}{2}}\, dW$

and $F(W) = 1 - \dfrac{1}{e^{(W - W_F)/kT} + 1} = \dfrac{1}{1 + e^{(W_F - W)/kT}}$

$= e^{(W - W_F)/kT}$ Since $(W_F - W)$ is large greater than kT.

$$n_h = 4\pi\left(2m_h^*/h^2\right)^{3/2} e^{-W_F/kT} \int_{-\infty}^{0} (-W)^{\frac{1}{2}} e^{W/kT}\, dW.$$

$$= 4\pi\left(2m_h^*/h^2\right)^{3/2} e^{-W_F/kT} \pi^{\frac{1}{2}}/2\,(kT)^{3/2}$$

$$\text{or} \quad n_h = 2(2\pi m_h^* kT/h^2)^{3/2} e^{-W_F/kT} \qquad \ldots\ldots\ldots\ldots\ldots (26)$$

Therefore, from Equations (25) and (26) we have,

$$n_h n_e = n_i^2 = 4\left(2\pi kT/h^2\right)^{3} \left(m_e^* m_h^*\right)^{3/2} e^{-W_g/kT}$$

from which $n_i = 2(2\pi kTm/h^2)^{3/2} e^{-W_g/2kT}$

$$= 5 \times 10^{21}\, T^{3/2} e^{-W_g/2kT} \qquad \ldots\ldots\ldots\ldots\ldots (27)$$

if $m_e^* = m_h^* = m$ is assumed.

3.9 RESISTIVITY

The resistivity, ρ is measured in ohm - m by

$$\rho = \frac{VA}{IL} \qquad \ldots\ldots\ldots\ldots\ldots (28)$$

where V = voltage drop in volts

I = current in Amperes

A = cross section of the sample in m^2

L = distance between probes in meter.

At high temperatures instrinsic conduction occurs where $n_e = n_h = n_i$ as the electrons leaving the valence band making the same number of holes.

At lower temperatures, resistivity depends on the impurity content.

The resistivity of semi-conductors decreases with the increase of temperature as the electron and hole concentration arise from the filled to the conduction band. The theory indicates that

$$\rho = A\ e^{W_g / 2kT} \qquad \text{.....(29)}$$

where A = a constant

k = bolts man's constant

T = temperature in ^{o}K

W_g = energy gap between the top of the filled band and the bottom of the conduction band.

From a resistivity versus temperature curve A & W_g can be calculated.

3.10 MAGNETO - RESISTANCE

Variation of resistivity of a specimen of semi-conductor in a magnetic field is an important phenomenon and is denoted simply by $\frac{\rho-\rho_o}{\rho_o} \times 100 = \frac{\Delta\rho}{\rho_o} \times 100$ where $\Delta\rho$ = change in resistivity with and without the magnetic field, ρ_o = resistivity at zero magnetic feild.

From the work of Kapitza it is known that the magnitude of the change of resistance depends upon the value of $\frac{e H \tau}{m}$, where τ is the relaxation time. From this we find that if the electrons have the same relaxation time τ and mass m, they will suffer the same effective Lorentz Force F, which will be balanced exactly by the electrostatic force $e F_H$. Consequently the electron paths will be essentially unchanged in the new dynamic equilibrium, and therefore the current and conductivity will be unaltered. That is to say that there will be no magneto-resistance.

CHAPTER - 4

DESCRIPTION OF THE EQUIPMENT

4.1 THE ELECTROMAGNET

An electromagnet constructed by D.J. Syam[33] was used. The design was re-checked and results obtained differred a bit from the theory. The electromagnet consists of :

1) Air gap.
2) Poles pieces of mild steel.
3) Yoke of cast iron.

It is desired to produce a magnetic flux density of 1 weber/ m^2 in the air gap.

1) Magnetic field intensity in the air gap ,

$$H_1 = \frac{B}{\mu_0 \mu_r} = \frac{1}{4\pi \times 10^{-7}} = 7960 \text{ AT/cm.}$$

$$F_1 = H_1 L_1 = 7960 \times 2 = 15{,}920 \text{ AT.}$$

2) Neglecting fringing , Since the diam of pole pieces (10 cm.) is much greater than the length of the air gap (2 cm.)

We have , $\phi_2 = B_2 A_2 = B_1 A_2 = 1 \text{ weber/ } m^2 \times A_2$

$= 10^4 \text{ lines / } cm^2 \times 78.3 \text{ } cm^2 = 78.3000 \text{ lines}$

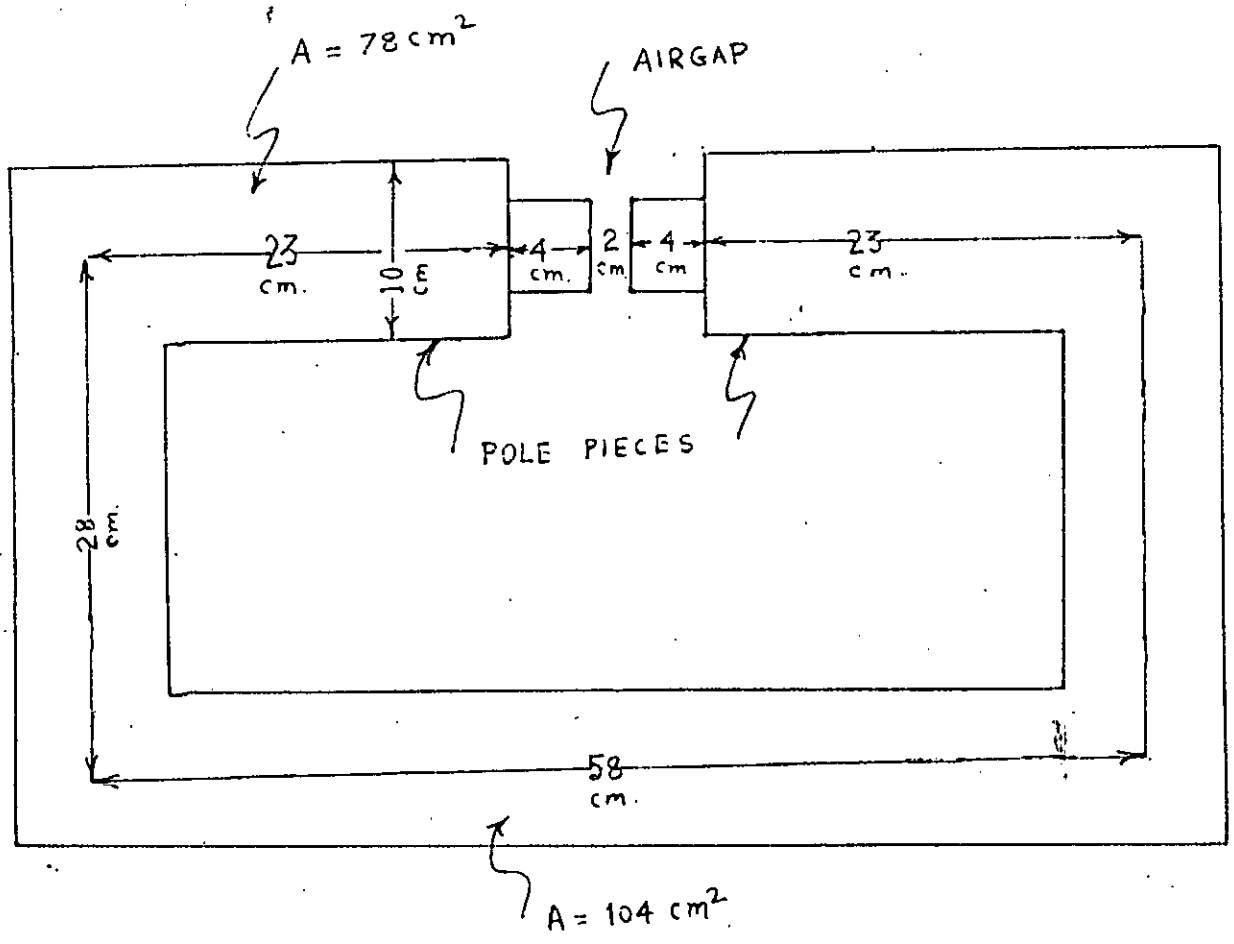
B_2 (in pole pieces) = 783,00/ 78.3 = 10^4 lines/ cm^2

H_2 (from B - H curve for mild steel[34]) = 13 AT/ cm.

$F_2 = H_2 L_2 = 13 \times (2 \times 27) = 702$ AT

3) ϕ_3 in the yoke = 783,000 lines (neglecting fringing)

$$B_3 = \frac{\phi_3}{A_3} = \frac{783{,}000}{104} = 7{,}520 \text{ lines / } cm^2$$



DIMENSIONS OF THE ELECTROMAGNET

Fig. 3.

H_3 (from B - H curve for cast iron[34]) = 49 AT/cm

$F_3 = H_3 L_3 = 49 \times (56 + 58.5) = 5600$ AT.

Hence total ampere-turns = 15,920 + 702 + 5,600 = 22222 AT

But the actual number of turns provided

$= T_1 + T_2 = 3990 + 3990 = 7980$ turns.

The coils were connected in series.

Hence, current required theoretically to produce a flux density of 1 weber/ m^2 = 22,222/ 7,980 = 2.77 Amperes. But it was seen that in experiemnt only 0.75 weber/ m^2 was obtained at a current flow of 2.77 Amperes.

4.2 THE FLUXMETER

The Scalamp fluxmeter made by Scientific PYE Instrument Co. was energised from a 4 volt battery. There were two coils for the measurement of the flux density in the air gap of the electromagnet. After the connection the coil was moved into the air gap and the reading was taken on the scale. Before taking such measurement, zero adjustment was made.

The specification of the fluxmeter used is given below :

CAT No. 8834

F.S.D. 0.007 WEB-TURN

Search Coils : 1 { 10.1 cm^2 -Turns. / 1 cm = Mean Diam.

2 { 100 cm^2- Turns / 1 cm = Mean Diam.

Galvanometer Constants : Free period = 19 secs.

Critical damping resistance = 17 Kilo ohm

Current sensitivity = 1,590 mm/ μ A

4.3 THE SAMPLE HOLDER

The sample holder consists of (a) a wooden frame provided with (b) 3 Hall probes attached with 3 screws and the 4th probe is a brass plate upon which the sample is placed vertically as shown in the fiqure 4. The specimen of the semi-conductor with the sample holder was placed in the air gap of the electromagnet. No part of the sample holder was however, made of magnetic material. Brass nails were used in the wooden frame. The probes were made up of platinum material procured from Chemical Engineering Department and was attached with adjustable screws.

The probes were bought in and out of the holder by rotating the screws inside the nuts attached to the wooden frame. The contacts made with the samples were of course, pressure contacts.

4.4 THE POTENTIOMETER

The pptentiometer made by Leads & Northrup Company, was used for Hall voltage measurement. There were two ranges (a) High range 0- 1.6 V. and (b) Low range 0- 16 mV. Both the ranges were used for different measurements. The proper range was selected by connecting the negative supply of E.M.F. to terminal 1 for 0- 1.6 V range or to terminal.01 for 0 - 16 millivolts range.

4.5 3 DIAL RESISTANCE BOX

The 3 step resistance box was not enough for an accurate balance. 4 - step resistance box was needed to obtain an accurate balance but unfortunately it was not available in our laboratory.

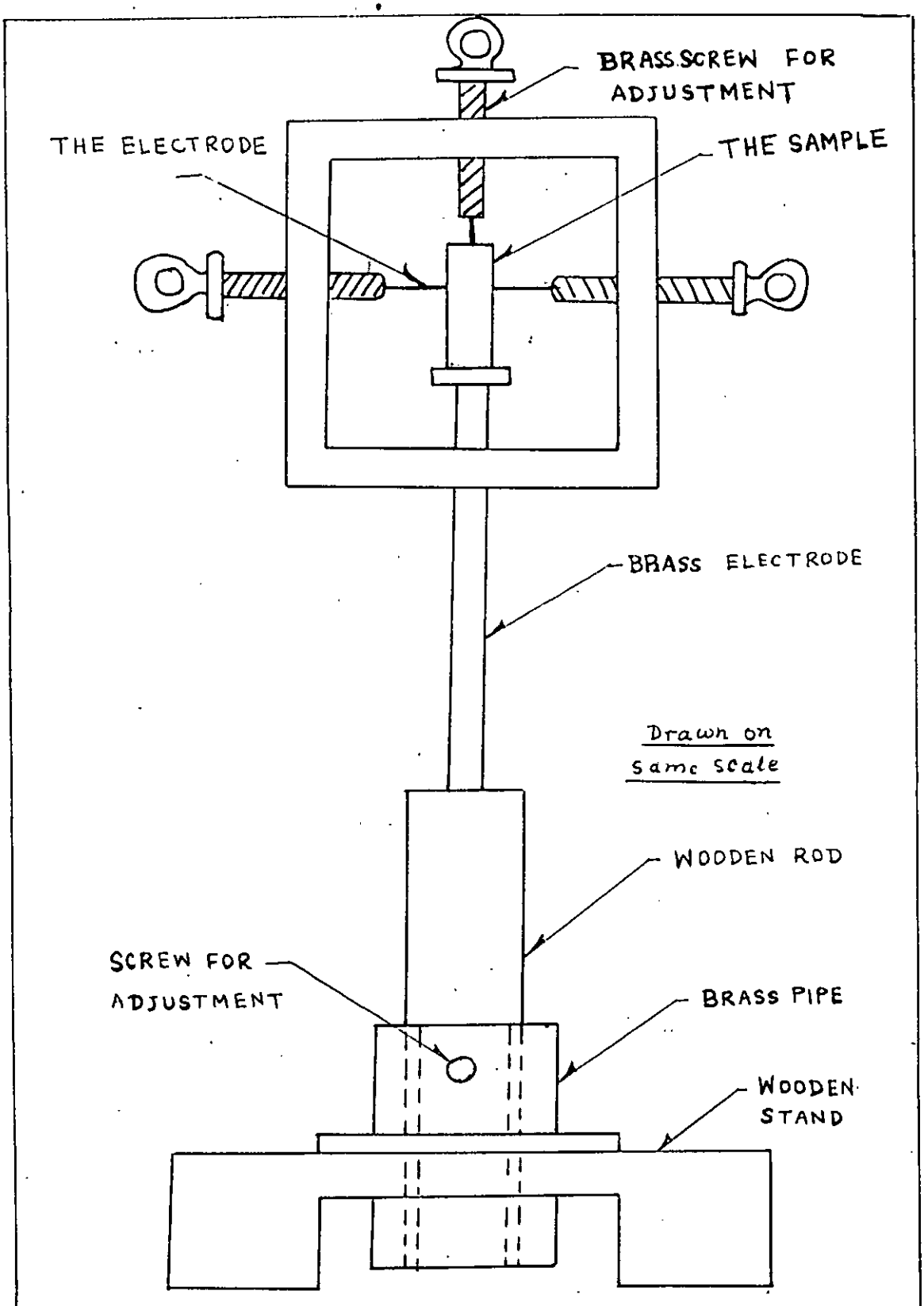


Fig. 4.
THE SAMPLE HOLDER

4.6 GALVANOMETER

This was an important equipment for Hall voltage measurement. Non-availability of a galvanometer with sufficient sensitivity was a great obstucle in the way of the measurement of Hall voltage accurately. No highly sensitive D.C. galvanometer was available. However a scalamp galvanometer of sensitivity .008 μ A/mm was used.

4.7 MICROAMMETER

A microammeter (0 - 150 - 300 - 500) was connected between the Hall probes and used for checking the polarity of the voltage drop across the probes.

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CHAPTER - 5

EXPERIMENTAL SET - UP

5.1 CALIBRATION OF ELECTROMAGNET

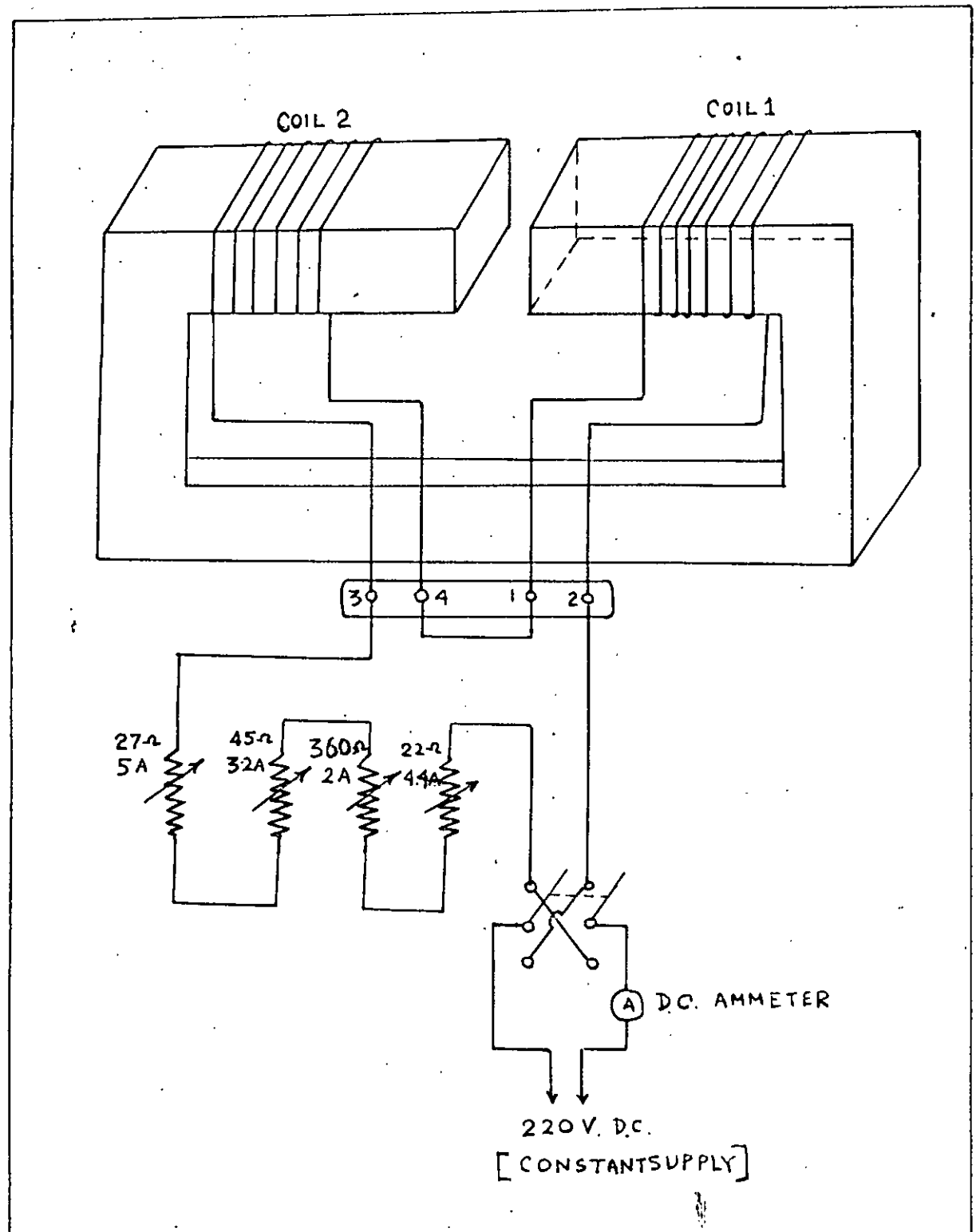
The coils of the electromagnete were connected in series as shown in figure 5. Magnitude of the current through the coils was changed from zero to maximum (5 Amp.) and the flux density of the air gap was measured by flux meter. With no current a flux density of about 0.02 web/ m^2 was observed. This is accounted for residual magnetism. A B - I curve was drawn in fig.8. Saturation was observed at a current flow of 5 amperes.

5.2 PREPARATION OF THE SAMPLES

A number of natural Pakistani ores were collected from the Head, Mining Engineering Department, West Pakistan University of Engineering and Technology. The ores were cut into rectangular pieces with a saw and its surfaces were polished highly by grinding machine, stone and lastly by emery paper. The thickness of the samples was reduced to the minimum in order obtain a measurable value of Hall voltage. The length to width ratio of the samples was made around three, as it gave maximum Hall effect according to Isenberg Theory [35].

5.3 MEASUREMENT OF HALL VOLTAGE

An electromagnet of high field intensity shown in the figure 5 was used. The magenetwas a large air cooled electromagnet having a capacity of 5 amperes. It had a field strength as high as 10 kilogauss (1 web/ m^2) .



CIRCUIT DIAG. FOR THE CALIBRATION OF ELECTROMAGNET

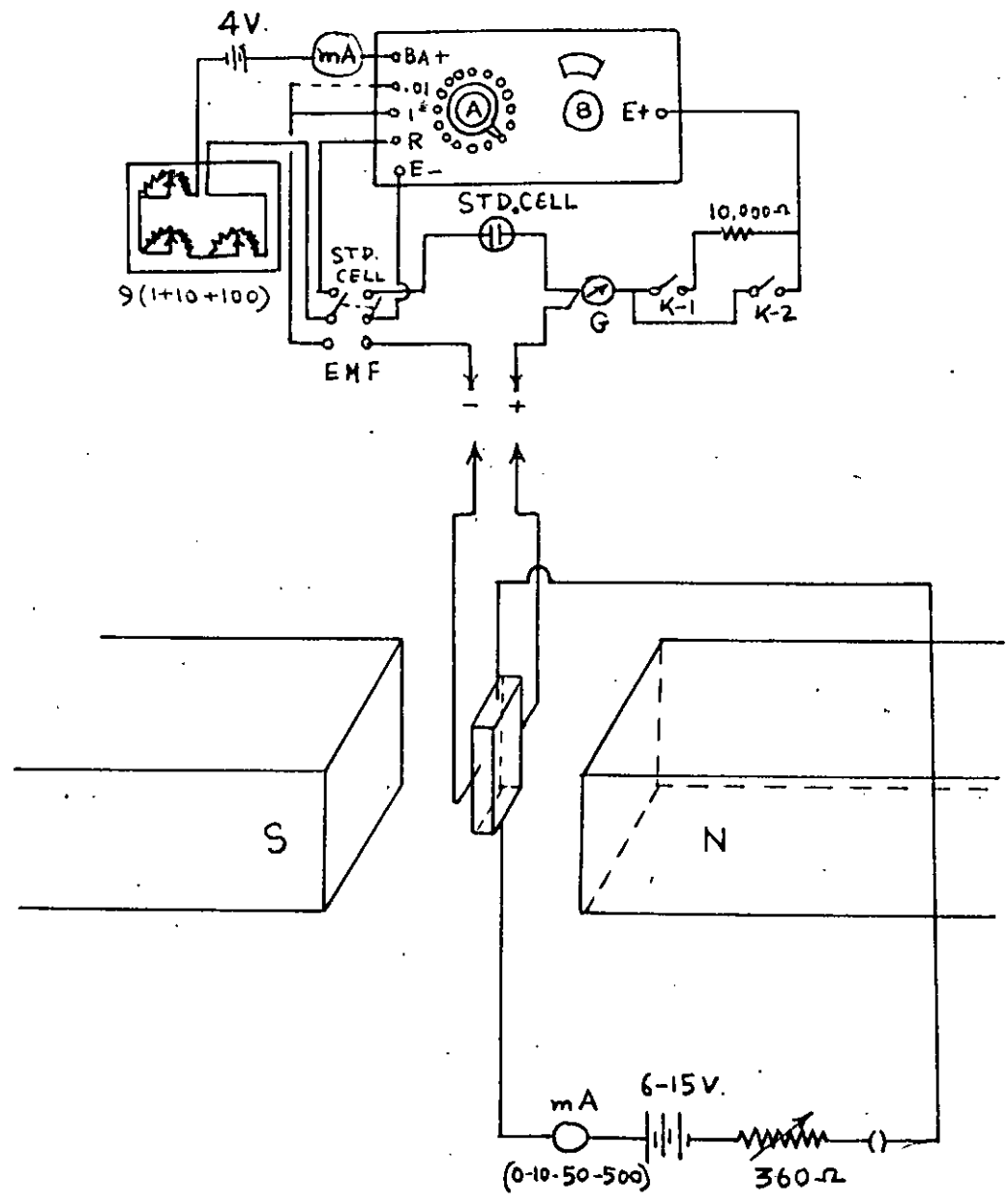
Fig. 5

The electromagenet was energised from a 220 volt D.C. supply. A D.C. ammeter was used to measure the current flowing through the coils. A D.P.D.T. switch was used for reversing the direction of the current flow through the coils.

The sample holder was constructed in such a way that it could be used for different samples to be studied. The details of the construction of the sample holder is shown in figure (4). The electrodes were made up of platinum wire. Hall probes were fitted in such a way that two of them could be moved horizontally and the other vertically with the help of screws. The crystal was placed on the round brass plate and fixed by the electrodes properly for good surface contact. The horizontal probes were aligned in the same horizontal line. The circuit for the measurement of Hall voltage is shown in the figure 6.

POTENTIOMETER : The students' potentiometer was used for the measurement of Hall voltage. 1.6 mV. range was used. Careful attention was given to the polarity markings and to the use of 10,000 ohm protecting resistor for the standard cell as well as the galvanometer.

To standarise the potentiometer, D.P.D.T. switch was thrown over to the standard cell position and then the dial switch A and knob B were turned to the position of the voltage of the standard cell. The key- 1 was pressed and released, and at the same time the galvanometer diffection was noted. The current drawn from the battery was found to be about 10 mA under balanced condition. Before taking any measurement, a few minutes were allowed in order to stabilise the current in the potentiometer.



MEASUREMENT OF HALL VOLTAGE

Fig. 6

If the K = 1 or K = 2 is made on without turning A & B to the position of the voltage of the standard cell, heavy current will be drawn from the cell, thereby damaging it. If such thing happens, by chance, sufficient time must be allowed until the voltage of the standard cell regains. After the standardisation, the D.P.D.T. switch was thrown on to the E.M.F. position and the Hall voltage was measured.

5.4 MEASUREMENT OF RESISTIVITY

Resistivity was measured by measuring the potential drop across two probes separated by a distance. The potential drop was measured with the help of a potentiometer. Circuit diagram for the measurement of resistivity is shown in figure 7.

5.5 MAGNETORESISTANCE

The same crystal holder was used for the measurement of magneto resistance of the samples. The change of current through the crystal was observed for samples placed in magnetic field. The change of resistance was calculated in each case by using the formula

$$\rho_m = \frac{\rho - \rho_0}{\rho_0} \times 100 = \frac{\Delta\rho}{\rho_0} \times 100$$

where ρ_m = magneto resistance expressed in percentage.

ρ = resistance of the sample in magnetic field.

ρ_0 = resistance of the sample in the absence of magnetic field.

A compass needle was used to measure the direction of magnetic field.

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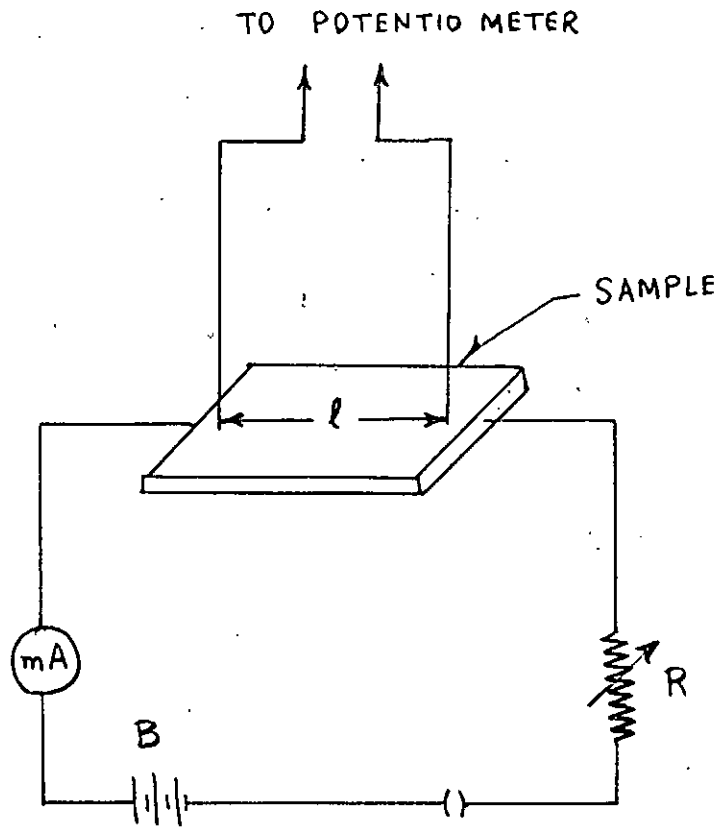


THE MEASERMENT OF RESISTIVITY

Fig. 7

5.6 WORKING FORMULAE

1. Number of atoms/ unit volume = $\frac{\text{Number of atoms / unit cell}}{\text{Volume of unit cell}}$

2. Hall effect - a) Impurity range

1. $R_H = \pm \frac{E_y}{B_z J_x}$

2. $n = \pm \frac{3\pi}{8 R_H e}$

3. $\sigma = ne\mu$

4. $\theta_H = R_H B_z \sigma$.

5. $\mu_h = \pm \frac{8}{3\pi} \sigma R_H$.

b) Intrinsic range (ideal)i.e. $n_e = n_h$)

1. $R_H = \frac{3\pi}{8 e n_i} \frac{1-c}{1+c}$ where $c = \frac{\mu_e}{\mu_h}$

2. $n_i = \frac{3\pi}{8e R_H} \frac{1-c}{1+c}$

3. $\sigma = e n_i \mu_h (c + 1)$

4. $\mu = (\pm -c)\mu_h$ where μ = apparent mob.

5. $n_i = 5 \times 10^{21} T^{3/2} e^{-W_g/ 2 kT}$

c) Instrinsic range/(non-ideal $n_e \neq n_h$)

1. $R_H = \frac{3\pi}{8e} \frac{n_h \mu_h^2 - n_e \mu_e^2}{(n_h \mu_h + n_e \mu_e)^2}$

2. $n_h = \frac{\sigma / e \mu_h + c n_s}{c + 1}$

3. $\sigma = e \mu_h (c n_e + n_h)$

4. $n_e n_h = 5 \times 10^{21} T^{3/2} e^{-W_g / 2 kT}$

3. Resistivity : $\rho = \frac{VA}{IL}$

4. Magneto resistance : $\rho_m = \frac{\rho - \rho_o}{\rho_o} \times 100$

$= \frac{\Delta \rho}{\rho_o} \times 100$

****

CHAPTER - 6

EXPERIMENTAL DATA

6.1 VARIATION OF MAGNETIC FIELD WITH CURRENT

No. of observation	Magnetising current in Ampere.	Magnetic flux density in web/m^2
1	0.0	0.02
2	0.7	0.219
3	1.0	0.315
4	1.5	0.50
5	2.0	0.65
6	2.5	0.74
7	3.0	0.80
8	3.5	0.83
9	4.0	0.86
10	5.0	0.90

The B - I curve is drawn in figure 8

CALIBRATION OF ELECTROMAGNET

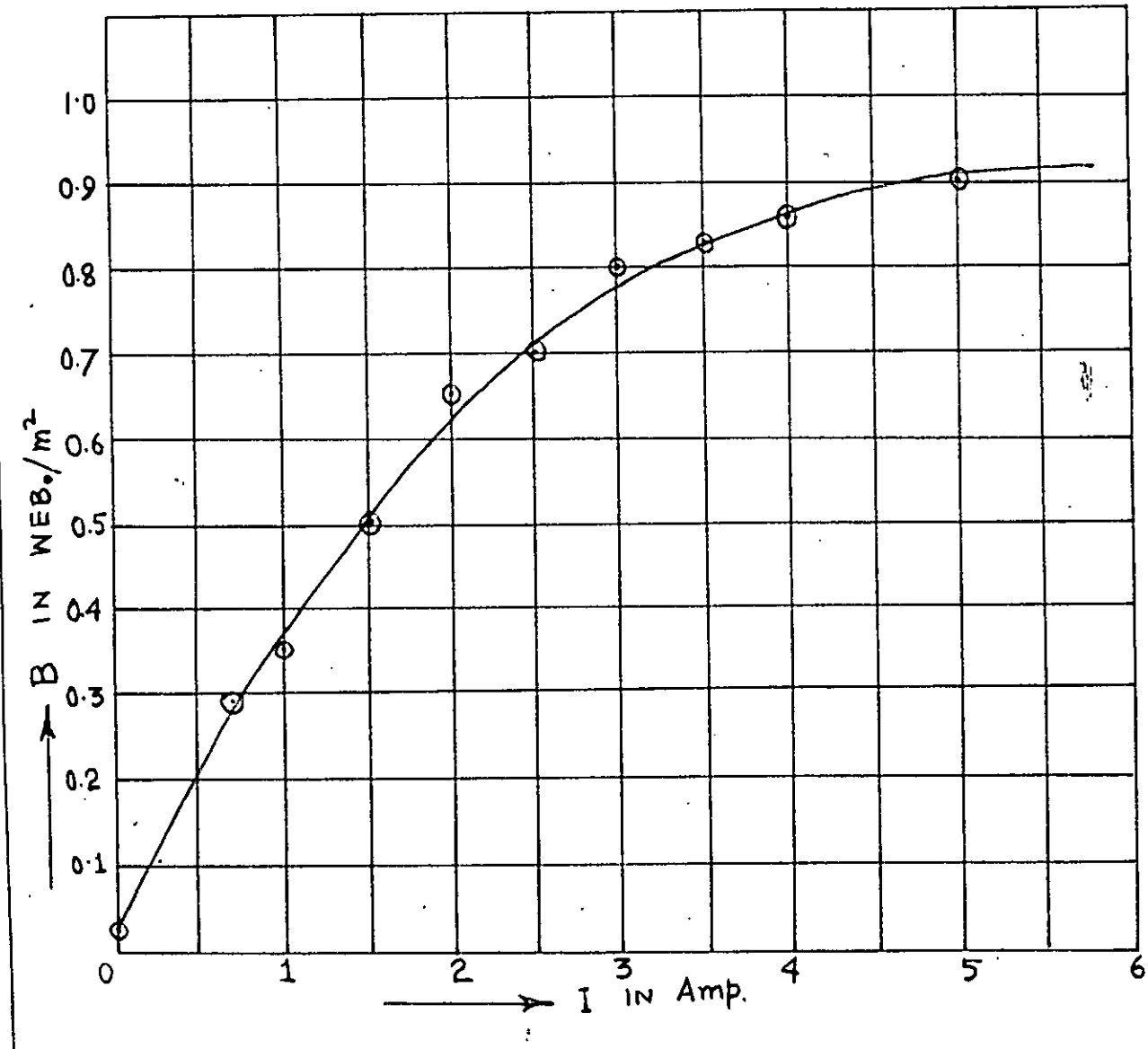


Fig. 8

6.2(i) SAMPLE - 1 STIBNITE ($Sb_2 S_3$)

TABLE - 1 (a)

VARIATION OF HALL VOLTAGE WITH CURRENT THROUGH CRYSTAL

Battery of potentiometer circuit = 4 Volt, R = 240 - 244 ohm.
standard cell = 1.01943 volt, current through battery = 9.4 mA
Dimension of the sample : L = 1.70 cm, W = 0.4 cm, t = 0.25 cm.

No. of Obs.	Magnetic field in web/ m^2	Current through crystal in mA	Voltage between Hall probes in mV.		Hall Voltage in mV	Hall co-eff. R_H in m^3/C	Mean R_H
			without magnetic field	with magnetic field			
1	.835	5.0	.070	.084	+.014	$+.84 \times 10^{-5}$	
2	.835	10.5	.124	.150	+.026	$+.744 \times 10^{-5}$	
3	.835	16.0	.182	.229	+.047	$+.88 \times 10^{-5}$	
4	.835	20.0	.240	.284	+.044	$+.66 \times 10^{-5}$	$+.759 \times 10^{-5}$
5	.835	32.0	.310	.400	+.070	$+.656 \times 10^{-5}$	
6	.835	40.0	.415	.512	+.097	$+.725 \times 10^{-5}$	
7	.835	55.0	.505	.650	+.145	$+.792 \times 10^{-5}$	

The V_H - I curve id shown in figure 9.

VARIATION OF HALL VOLTAGE WITH CURRENT IN Sb_2S_3

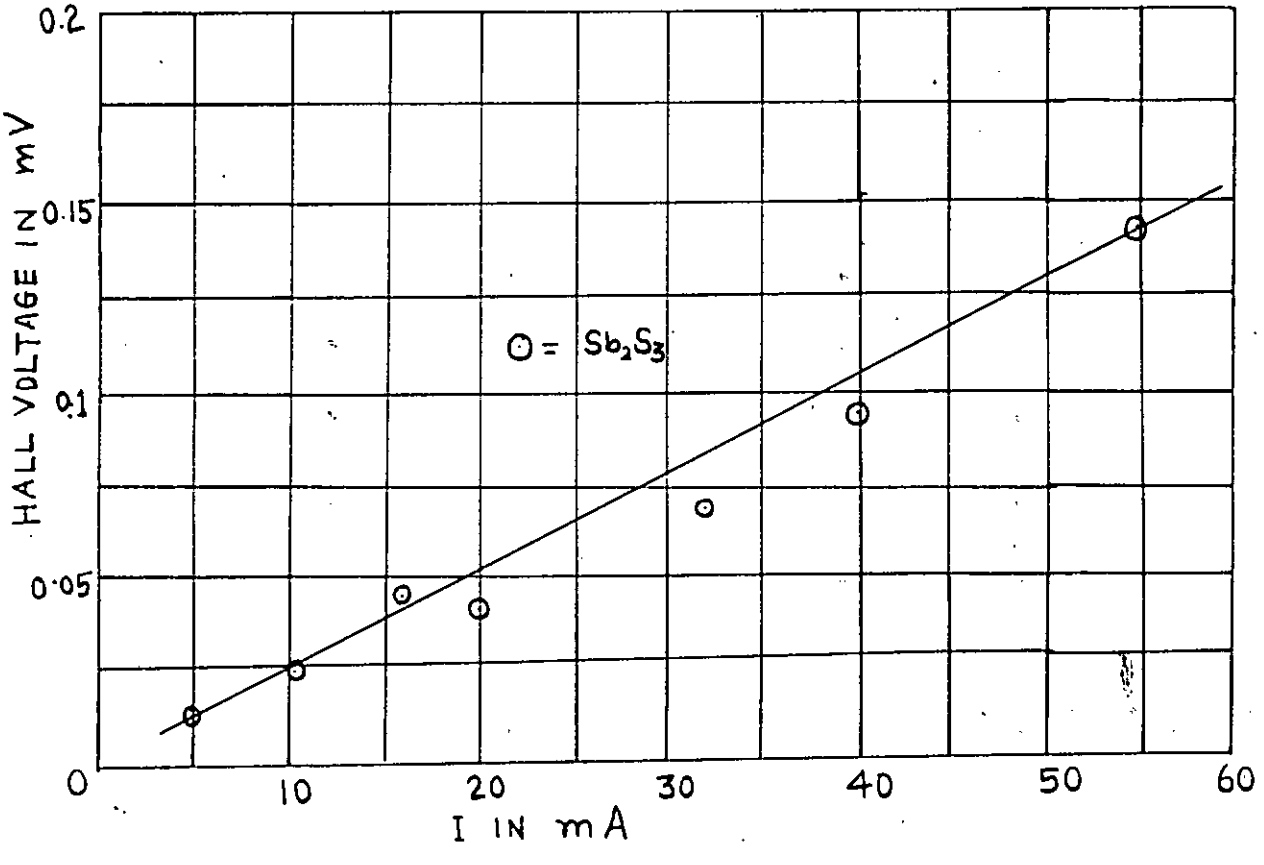


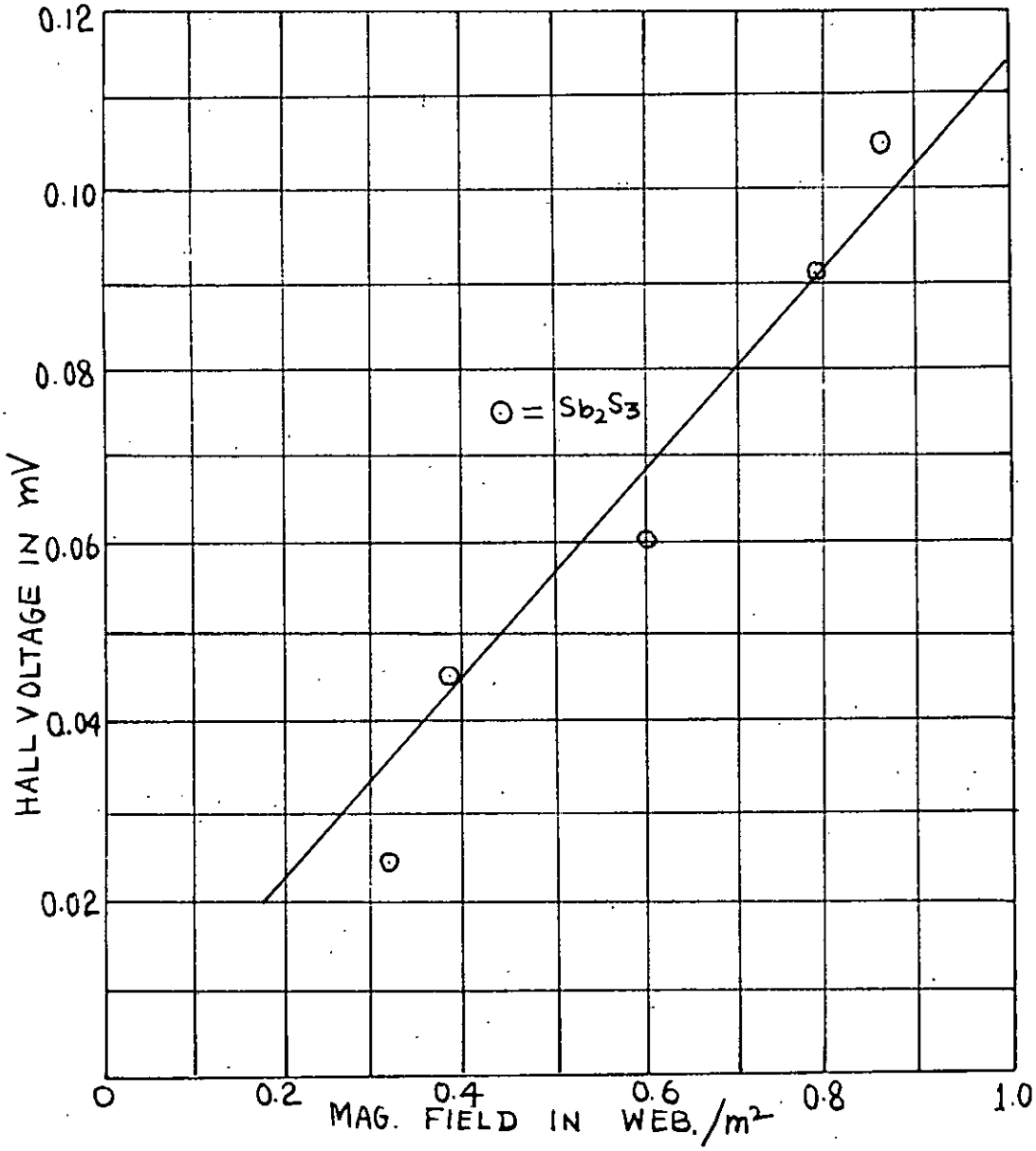
Fig. 3

TABLE -I (b)

VARIATION OF THE HALL VOLTAGE WITH MAGNETIC FIELD

No.of obs.	Magnetic field in web/ m^2	Current through crystal in mA	Voltage between Hall probes in mV		Hall Voltage V_H in mV	Hall co-eff. R_H in m^3/C	Mean R_H
			without magnetic field	with Magnetic field			
1	.31	45	.500	.524	.024	$.430 \times 10^{-5}$	
2	.37	45	.400	.445	.045	$.677 \times 10^{-5}$	
3	.60	45	.425	.485	.060	$.556 \times 10^{-5}$	$.598 \times 10^{-5}$
4	.79	45	.450	.542	.092	$.650 \times 10^{-5}$	
5	.86	45	.465	.570	.105	$.68 \times 10^{-5}$	

The graph is shown in figure 10.



VARIATION OF HALL VOLTAGE WITH MAG. FIELD IN Sb_2S_3

Fig. ~~10~~ 4

TABLE -1 (c)

VARIATION OF RESISTIVITY WITH CURRENT

Dimension of the sample : L = 1.7 cm , W = 0.4 cm, t = 0.25 cm

1) The sample was vergin i.e. sample was never placed in a magnetic field. Distance between probes = 1.7 cm

Number of observation	Current through the crystal in mA	Voltage drop across the probes in volt.	Resistivity in ohm m
1	0.4	0.427	0.632
2	0.7	0.525	0.442
3	1.0	0.597	0.352
4	1.5	0.683	0.268
5	2.0	0.748	0.2205
6	3.0	0.850	0.167
7	4.1	0.938	0.135
8	6.1	1.058	0.1023
9	8.0	1.140	0.084
10	10.5	1.235	0.0694

2) The resistivity was changed after the application of a magnetic field for a few minutes.

1	20.	0.645	1.9×10^{-2}
2	35	1.05	1.77×10^{-2}
3	65	1.82	1.65×10^{-2}
4	90	2.35	1.55×10^{-2}
5	170	3.60	1.25×10^{-2}

The graphs are shown in figures 11 and 12.

VARIATION OF RESISTIVITY WITH CURRENT IN Sb_2S_3

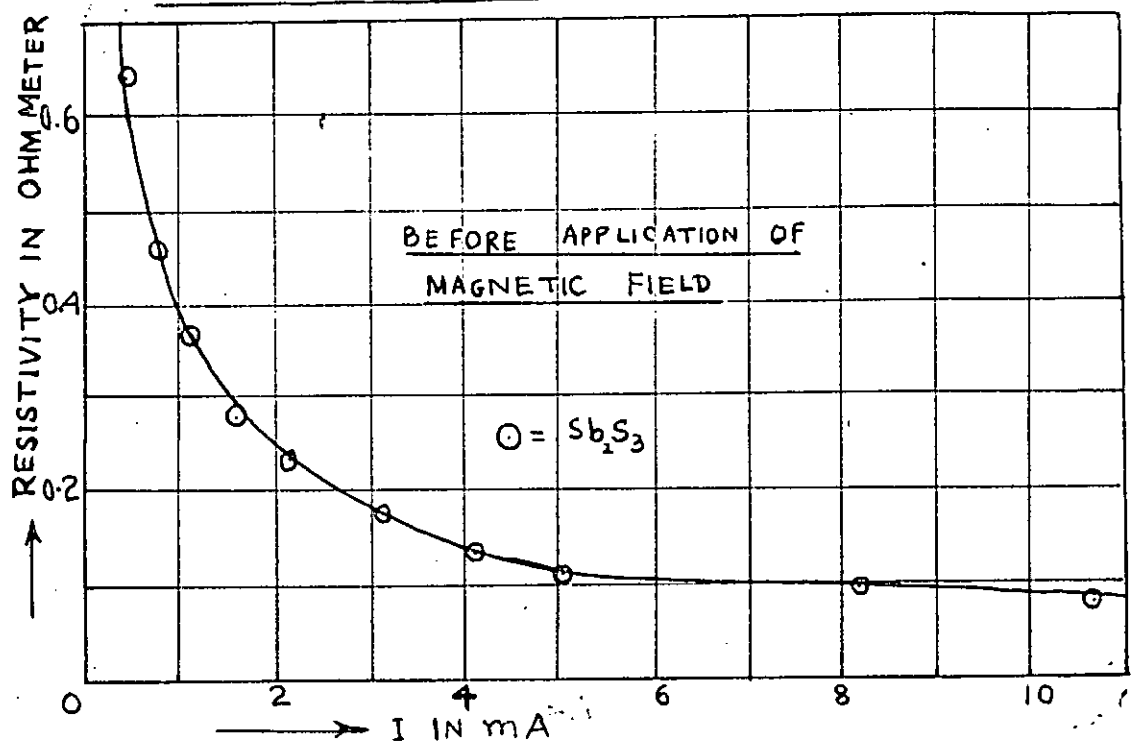


Fig. 11

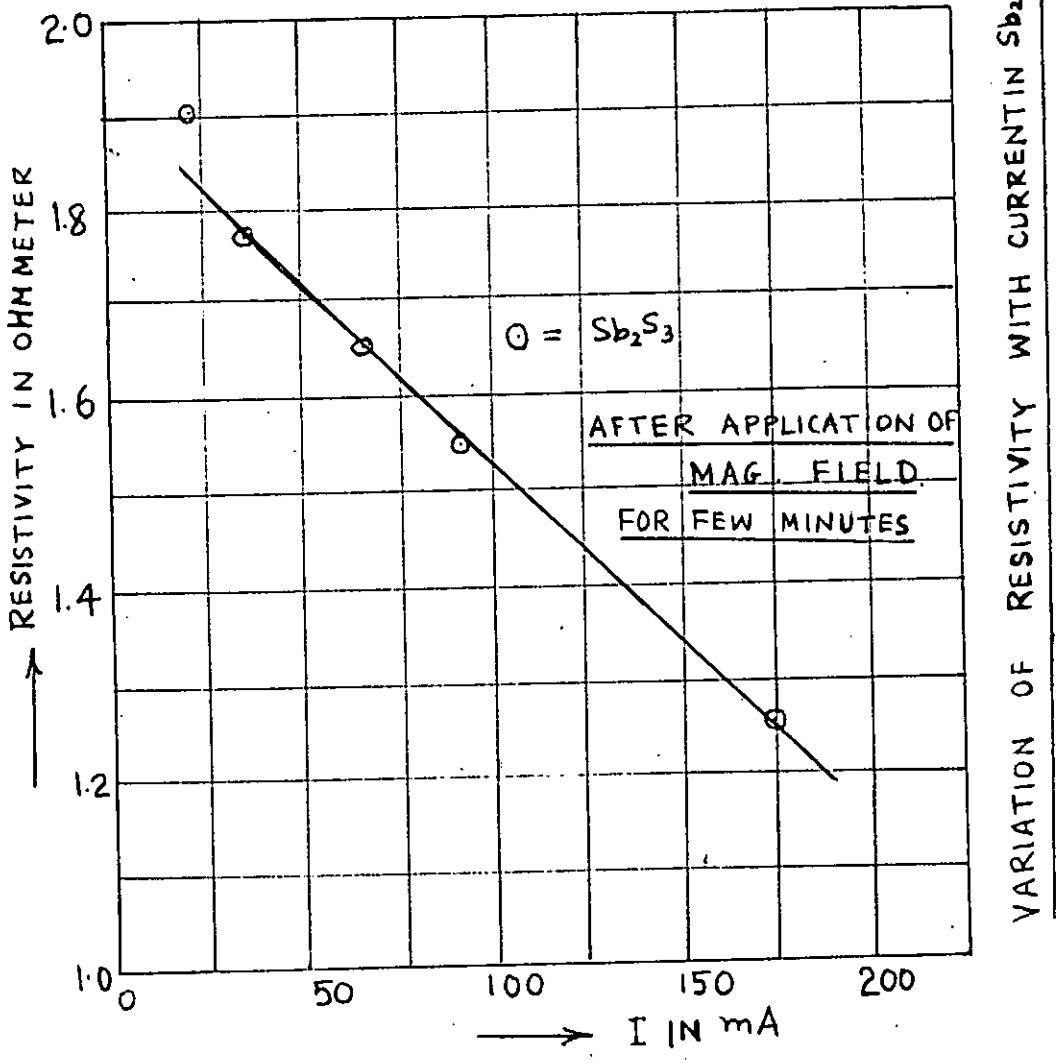


FIG. 12

TABLE -I (d)

MAGNETO- RESISTANCE

VARIATION OF RESISTANCE WITH MAGNETIC FIELD

The sample was first treated with a strong magnetic field.

Distance between probes = 1.7 cm

No.of obs.	Magnetic field in web/m^2	Voltage drop across the probes in volt	Current through the crystal in mA	Resistivity in ohm - m $\rho = \frac{A}{L}\frac{V}{I}$	Magnetoresistance $\rho_m = \frac{\rho - \rho_0}{\rho_0} \times 100$ in percent
1	.00	.115	4.90	$= 1.380 \times 10^{-2}$	0.00
2	.30	.115	4.88	$= 1.388 \times 10^{-2}$	0.58
3	.60	.115	4.85	$= 1.399 \times 10^{-2}$	1.38
4	.79	.115	4.82	$= 1.410 \times 10^{-2}$	2.17
5	.86	.115	4.80	$= 1.415 \times 10^{-2}$	2.54

The graph is shown in figure 13.

6.2(ii) SAMPLE - 2

LEAD SULPHIDE (PbS)

TABLE - 2 (a)

VARIATION OF HALL VOLTAGE WITH CRYSTAL CURRENT

Dimension of the sample : L = 1.3 cm , W = 0.8 cm, t = 0.43 cm

No. of obs.	Magnetic field in web/ m^2	Current through crystal in mA	Voltage between Hall probes in mV		Hall voltage in mV	Hall co-eff. R_H in m^3/C	Mean R_H
			Without magnetic field	With magnetic field.			
1	.6	1.1	6.265	6.445	.180	11.7×10^{-4}	
2	.6	2.1	11.765	12.155	.390	13.3×10^{-4}	
3	.6	3.2	18.000	18.350	.350	7.84×10^{-4}	10.47×10^{-4}
4	.6	4.0	22.750	23.265	.515	9.2×10^{-4}	
5	.6	5.1	27.625	28.325	.700	9.8×10^{-4}	
6	.6	6.2	33.710	34.660	.950	11.0×10^{-4}	

The graph is shown in figure 14.

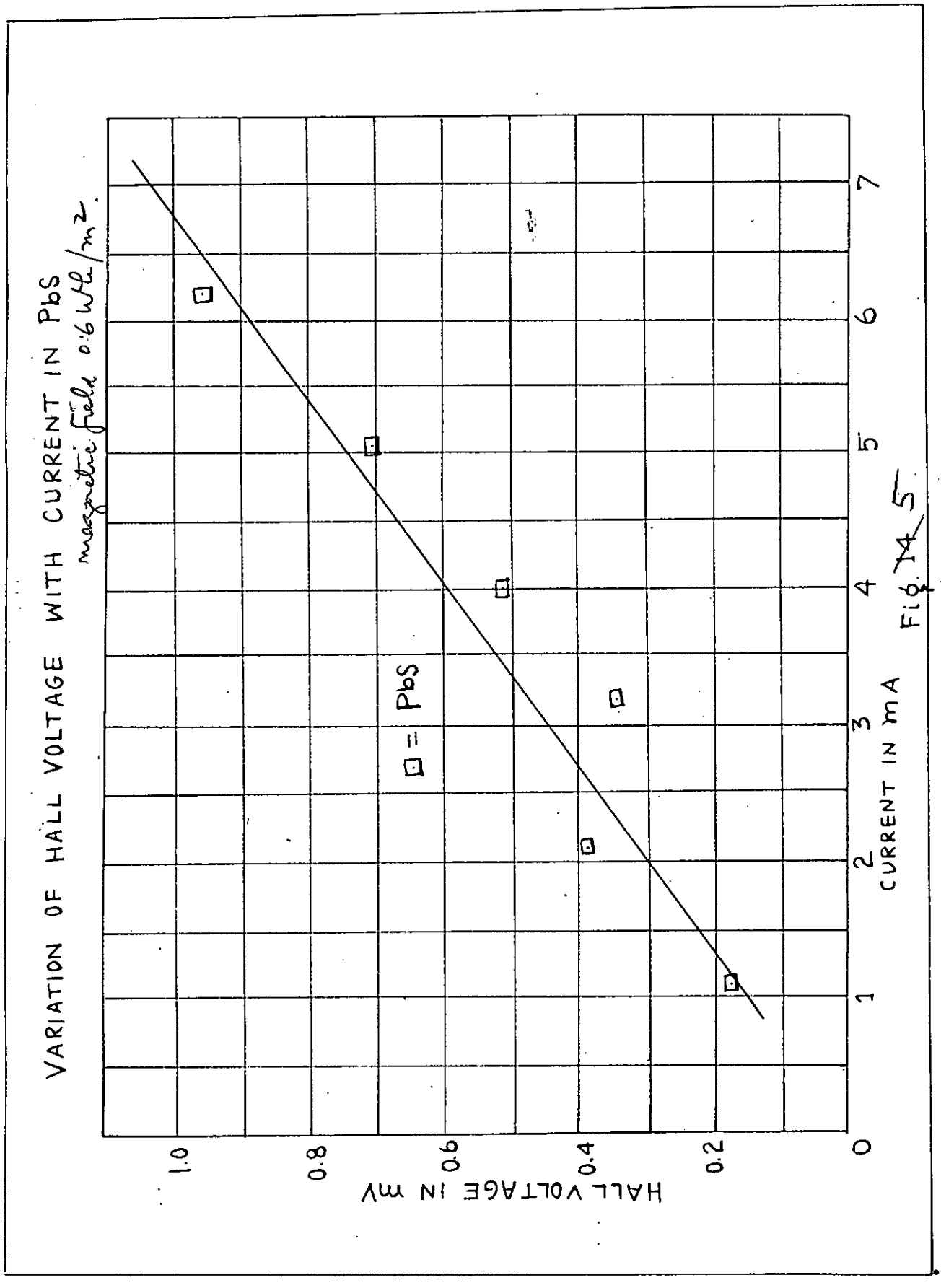

VARIATION OF HALL VOLTAGE WITH CURRENT IN PbS
magnetic field 0.6 wb/m²
□ = PbS
HALL VOLTAGE IN mV
0.2
0.4
0.6
0.8
1.0
CURRENT IN mA
0
1
2
3
4
5
6
7

Fig. 14.5

TABLE - 2 (b)

VARIATION OF HALL VOLTAGE WITH MAGNETIC FIELD

No. of obs.	Magnetic field in web/m^2	Current through crystal in mA	Voltage between Hall probes in mV		Hall voltage V_H in mV	Hall co-eff. R_H in m^3/C	Mean R_H
			Without magnetic field	With magnetic field			
1	.29	2.1	11.69	11.92	.23	16.2×10^{-4}	
2	.50	2.1	11.82	12.09	.27	10.6×10^{-4}	
3	.60	2.1	11.93	12.38	.45	15.3×10^{-4}	12.26×10^{-4}
4	.69	2.1	12.00	12.415	.415	12.3×10^{-4}	
5	.80	2.1	11.94	12.37	.43	11.0×10^{-4}	
6	.86	2.1	11.50	11.97	.47	11.2×10^{-4}	

The graph is shown in figure 15.

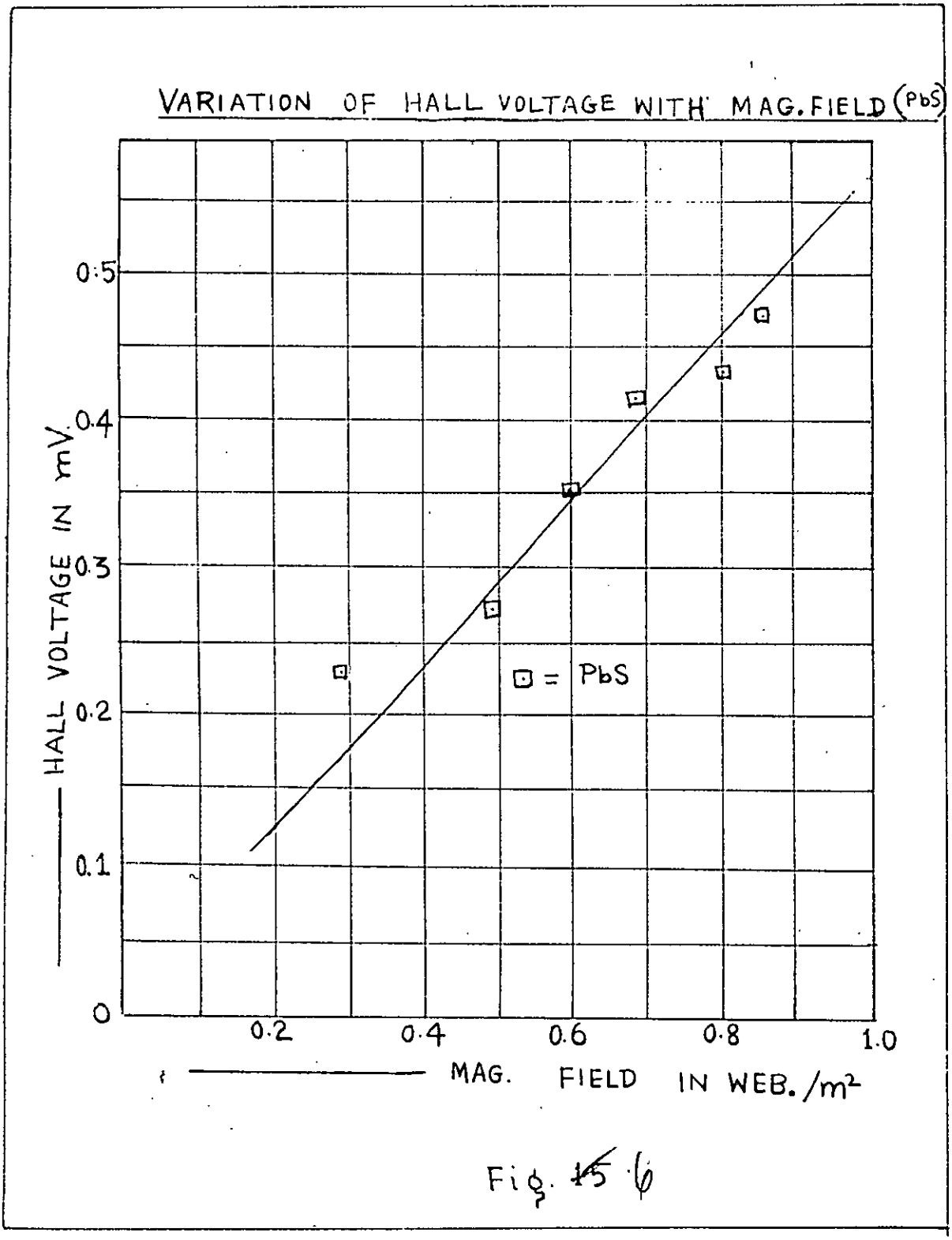

VARIATION OF HALL VOLTAGE WITH MAG. FIELD (PbS)
HALL VOLTAGE IN mV
0
0.1
0.2
0.3
0.4
0.5
□ = PbS
0.2
0.4
0.6
0.8
1.0
MAG. FIELD IN WEB./m²

Fig. ~~15~~ 6

TABLE - 2 (c)

MAGNETO RESISTANCE

VARIATION OF RESISTANCE IN MAGNETIC FIELD IN PbS

The sample was already treated in a strong magnetic field.

Distance between probes = 1.3 cm.

No.of obs.	Magnetic field in web/ m^2	voltage drop across the probes in volt	Current through crystal in mA		Resistivity in ohm - m		$\rho_m = \frac{\rho - \rho_0}{\rho_0} \times 100$ in percent
			without magnetic field	With magnetic field	With no magnetic field ρ_0	With magnetic field ρ	
1	.28	5.38	9.50	9.45	1.495	1.502	0.468
2	.31	5.38	9.50	9.44	1.495	1.503	0.545
3	.45	5.38	9.45	9.38	1.502	1.515	0.900
4	.64	5.38	9.35	9.22	1.519	1.540	1.385
5	.71	5.38	9.38	9.20	1.513	1.542	1.915
6	.83	5.38	9.32	9.075	1.525	1.565	2.600
7	.89	5.38	9.30	9.05	1.527	1.570	2.89

The graph is shown in figure 13.

TABLE - 2 (d)

VARIATION OF RESISTIVITY WITH CURRENT IN PbS

Distance between probes = 1.3 cm.

Number of observation.	Voltage drop across the probes in volt.	Current through the crystal in mA	Resistivity ρ in ohm - m
1	0.34	0.30	2.99
2	0.45	0.45	2.64
3	1.20	1.40	2.265
4	1.80	2.30	2.07
5	2.40	3.20	1.98
6	3.10	4.40	1.86
7	3.80	5.40	1.86
8	4.30	6.80	1.67
9	5.60	9.10	1.63

The graph is shown in figure 16.

VARIATION OF RESISTIVITY WITH CURRENT IN PbS.

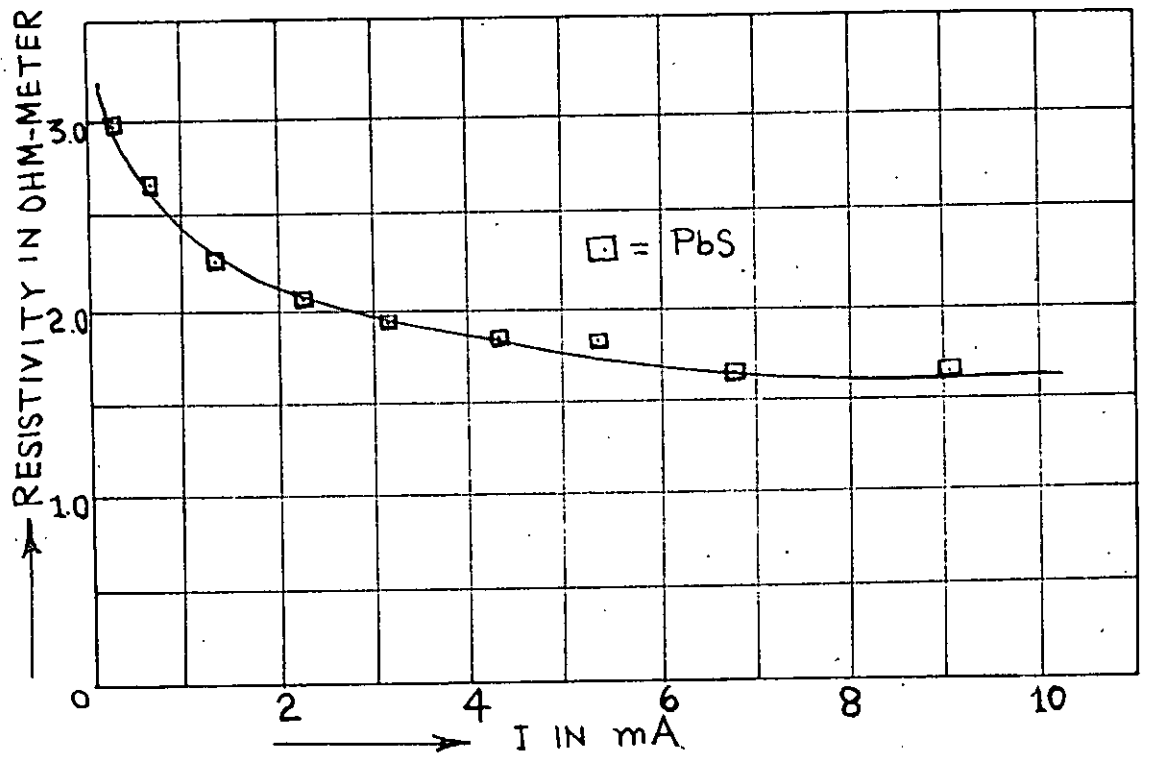


Fig. 16

6.2(iii) SAMPLE - 3

PYRITE ($F_e S_2$)

TABLE - 3 (a)

VARIATION OF HALL VOLTAGE WITH CURRENT IN PYRITE

Dimension of the sample : L = 1.4 cm, W = .6 cm , t = .6 cm.

No. of obs.	Magnetic field in web/ m^2	Current through crystal in mA	Voltage between Hall probes in mV		Hall voltage V_H in mV	Hall co-eff. R_H in m^3/C	Mean R_H
			With no magnetic field	With magnetic field			
1	.62	0.8	5.070	4.989	-.081	-0.98×10^{-3}	
2	.62	2.0	11.693	11.483	-.210	-1.015×10^{-3}	
3	.62	2.4	14.215	13.765	-.450	-1.82×10^{-3}	
4	.62	3.0	17.750	17.350	-.400	-1.29×10^{-3}	-1.36×10^{-3}
5	.62	4.0	20.600	24.000	-.600	-1.45×10^{-3}	
6	.62	5.0	31.230	30.450	-.780	-1.52×10^{-3}	
7	.62	5.6	36.520	35.682	-.838	-1.45×10^{-3}	

The graph is shown in figure 17.

VARIATION OF HALL VOLTAGE WITH CURRENT IN FeS_2

magnetic field 0·62 Wb/m².

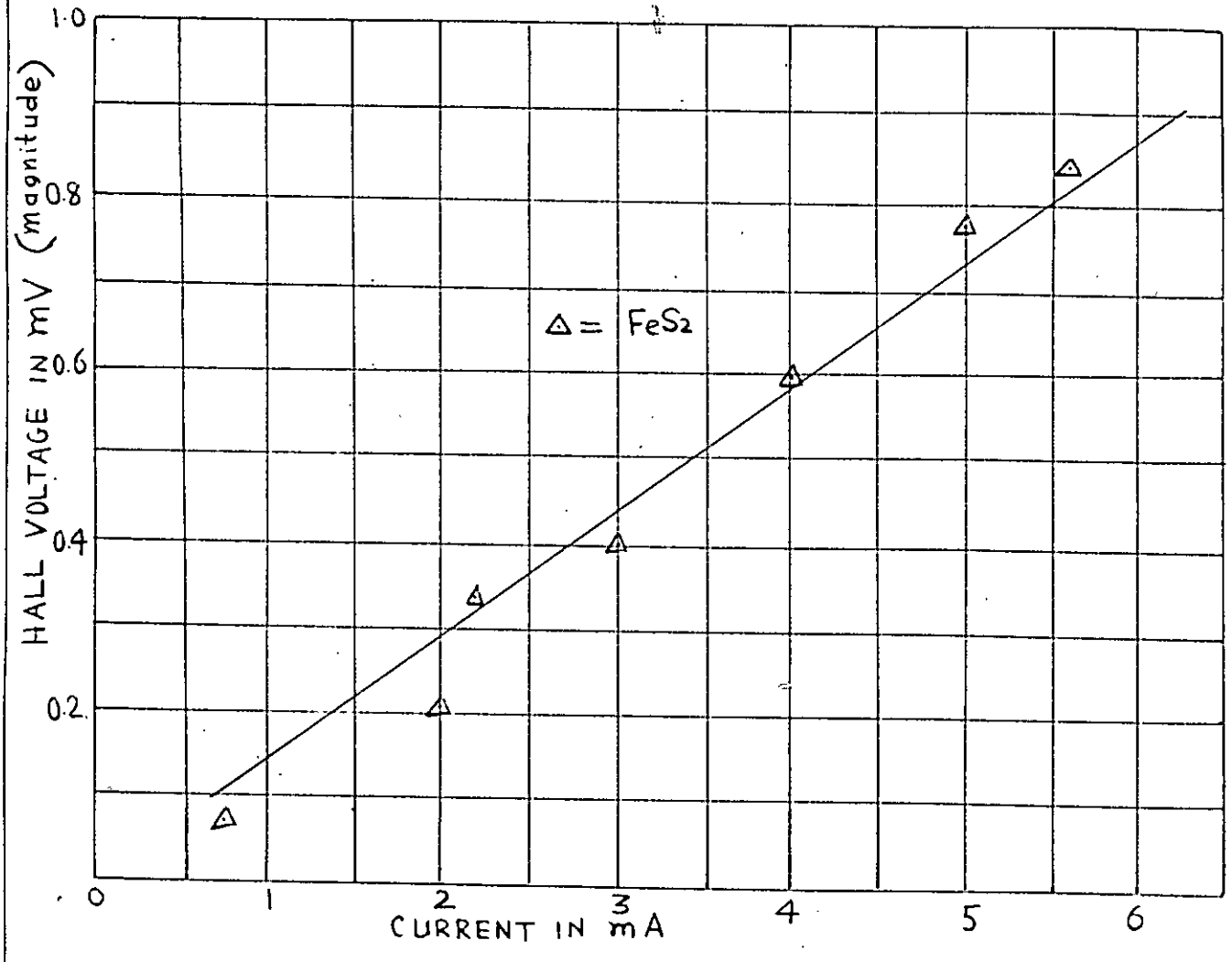


Fig. 17

TABLE - 3 (b)

VARIATION OF HALL VOLTAGE WITH MAGNETIC FIELD IN PYRITE

No.of obs.	Magnetic field in web/ m^2	Current through crystal in mA	Voltage between Hall probes in mV		Hall voltage V_H in mV	Hall co-eff. R_H in m^3/C	Mean R_H
			With no magnetic field	With magnetic field			
1	.31	2	8.344	8.154	.190	1.84×10^{-3}	
2	.50	2	8.532	8.282	.250	1.50×10^{-3}	
3	.62	2	8.012	7.732	.280	1.36×10^{-3}	1.62×10^{-3}
4	.78	2	8.470	8.010	.460	1.77×10^{-3}	
5	.86	2	8.625	8.155	.470	1.64×10^{-3}	

The graph is shown in figure 18.

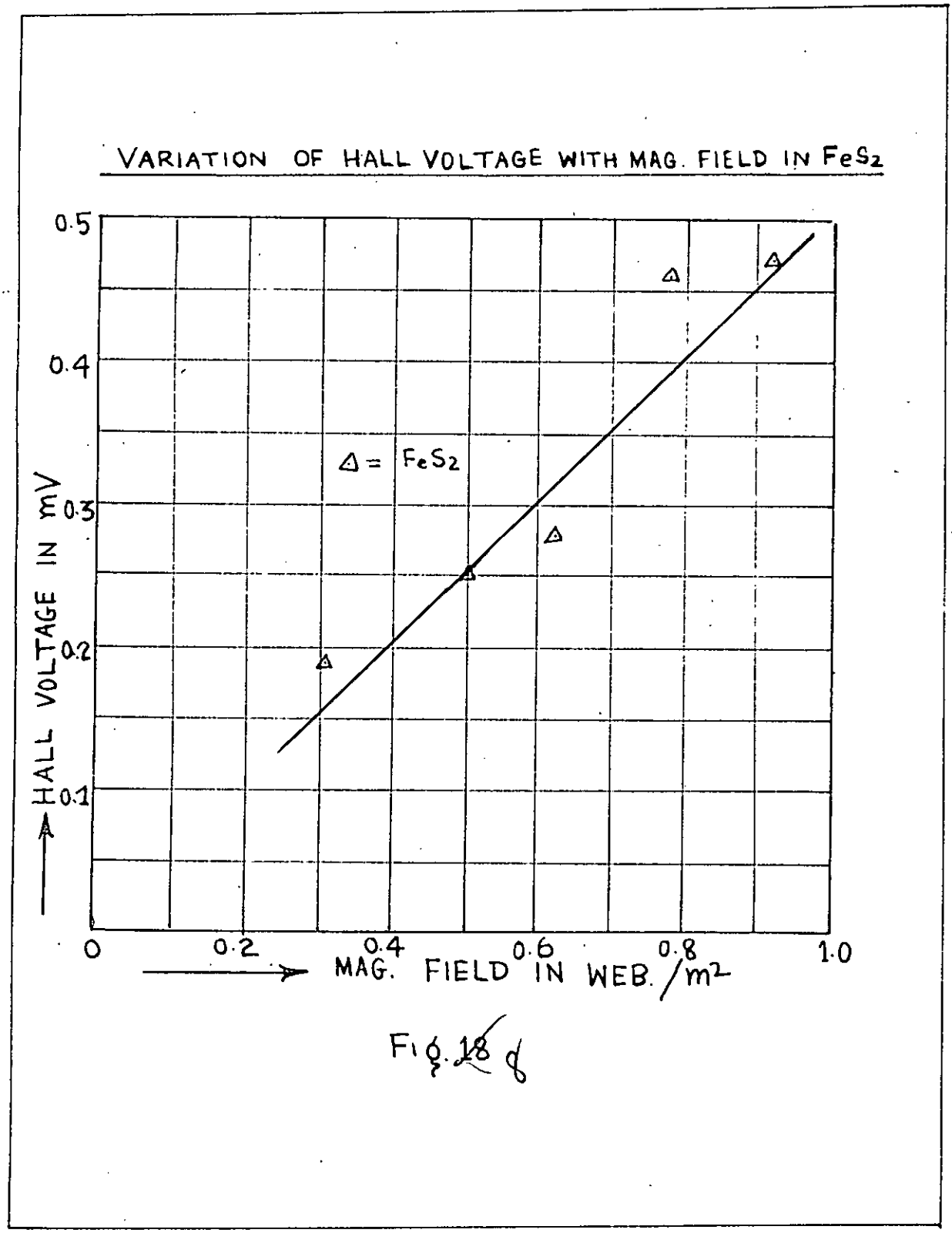

VARIATION OF HALL VOLTAGE WITH MAG. FIELD IN FeS_2
0.5
0.4
0.3
0.2
0.1
HALL VOLTAGE IN mV
Δ = FeS_2
0
0.2
0.4
0.6
0.8
1.0
MAG. FIELD IN WEB./m^2

Fig. 18 d

TABLE - 3 (c)

MAGNETO RESISTANCE

VARIATION OF RESISTANCE WITH MAGNETIC FIELD IN PYRITE

Distance between probes = 1.3 cm.

No.of obs.	Magnetic field in web/m^2	Voltage drop across the probes in volt.	Current through the crystal in mA		Resistivity in ohm meter		Magneto resistance $\rho_m = \frac{\rho - \rho_0}{\rho_0} \times 100$ in percent
			With no magnetic field	With magnetic field.	With no magnetic field ρ_0	With magnetic field ρ	
1	.28	5.6	2.450	2.410	5.875	5.970	1.62
2	.31	5.6	2.450	2.400	5.875	6.000	2.13
3	.41	5.6	2.450	2.395	5.875	6.030	2.64
4	.635	5.6	2.450	2.360	5.875	6.100	3.83
5	.72	5.6	2.450	2.350	5.875	6.140	4.52
6	.775	5.6	2.470	2.350	5.830	6.140	5.32
7	.83.	5.6	2.480	2.340	5.810	6.160	6.03
8	.875	5.6	2.480	2.330	5.810	6.180	6 375

The graph is shown in figure 13.

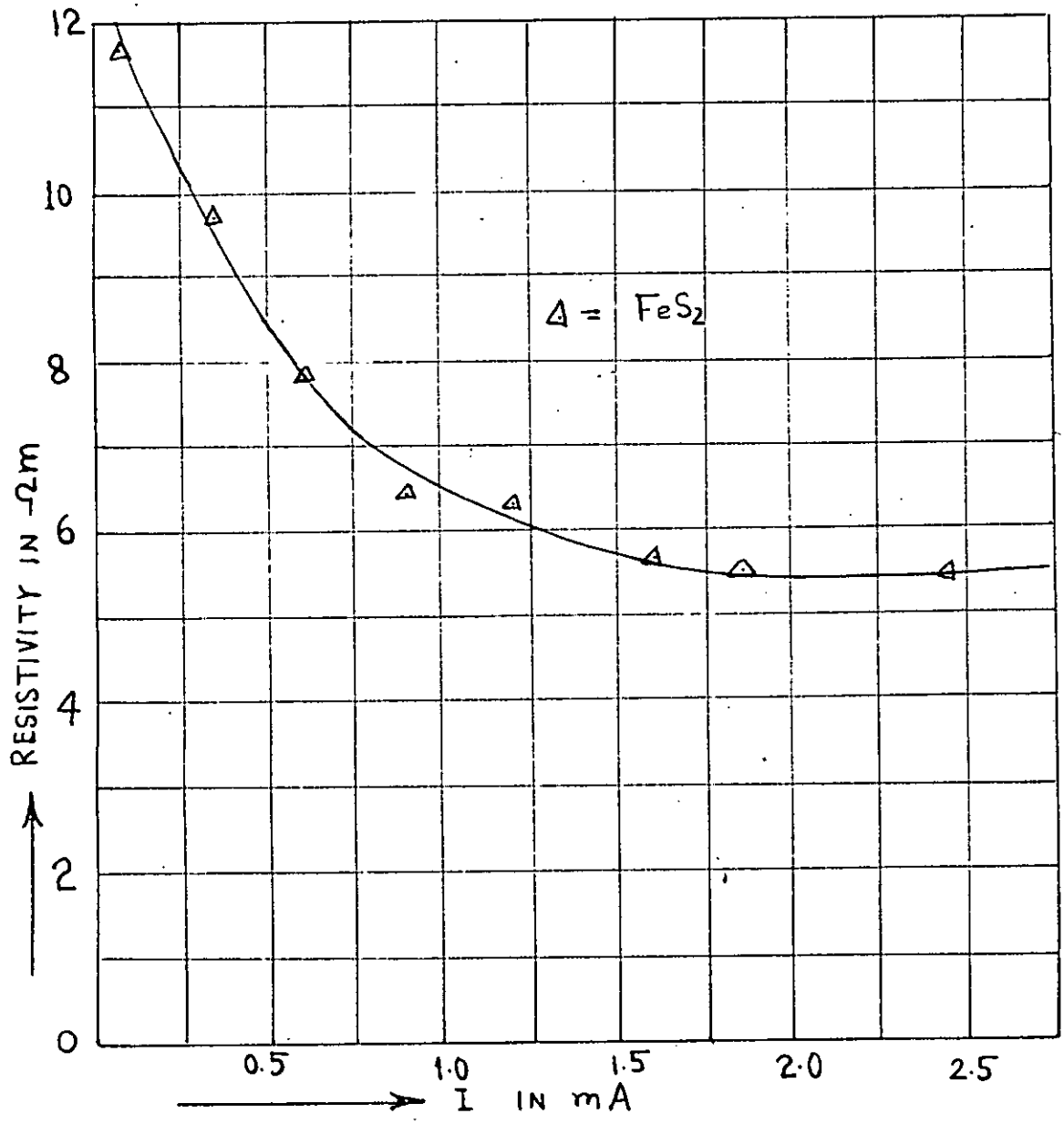
TABLE - 3 (d)

VARIATION OF RESISTIVITY WITH CURRENT IN PYRITE

Distan between probes = 1.4 cm.

Number of observation	Voltage drop across the probes in volt	Current through the crystal in m A	Resistivity in ohm - m
1	0.34	0.075	11.65
2	1.20	0.4	7.72
3	1.60	0.6	6.88
4	2.25	0.9	6.44
5	3.00	1.2	6.33
6	3.65	1.6	5.7
7	4.00	1.85	5.55
8	5.20	2.45	5.45

The graph is shown in figure 19.



VARIATION OF RESISTIVITY WITH CURRENT IN FeS_2

Fig. 19

CHAPTER - 7

RESULTS

7.1 CALCULATION OF NUMBER ATOMS PER UNIT VOLUME

a) $Sb_2 S_3$: $N = \frac{8 \text{ atoms} \times (100)^3}{(6 \times 10^{-8})^3} = 3.7 \times 10^{28}$ atoms/ m^3

b) PbS : $N = \frac{8 \text{ atoms} \times (100)^3}{(5.92 \times 10^{-8})^3} = 3.8 \times 10^{28}$ atoms / m^3

c) $F_e S_2$: $N = \frac{8 \text{ atoms} \times (100)^3}{(5.407 \times 10^{-8})^3} = 5.0 \times 10^{28}$ atoms / m^3

d) Nacl (Halite) : $N = \frac{8 \text{ atoms} \times (100)^3}{(5.63 \times 10^{-8})^3} = 4.46 \times 10^{28}$ atoms/m^3

e) Graphite : $N = \frac{4 \text{ atoms} \times (100)^3}{(2.4611)^2 \times 6.707 \times (10^{-8})^3} = 10.1 \times 10^{28}$ atoms/m^3

CAUTION : These values are approximate as the exact composition and purity of the ores were not known. By way of illustration, the values for G_e and S_i are given below :

f) G_e : $N = \frac{8 \text{ atoms} \times (100)^3}{(5.62 \times 10^{-8})^3} = 4.52 \times 10^{28}$ atoms / m^3

g) S_i : $N = \frac{8 \text{ atoms} \times (100)^3}{(5.43 \times 10^{-8})^3} = 5.0 \times 10^{28}$ atoms / m^3

7.2(i) STIBNITE (As Extrinsic Semi-conductor)

1) $n_h = 1.18 \times \frac{1}{5.98 \times 10^{-6} \times 1.6 \times 10^{-19}} = \underline{1.23 \times 10^{24}}$ Holes/m^3

2) $\mu_h = .85 \times \frac{5.98 \times 10^{-6}}{1.73 \times 10^{-2}} = \underline{2.935} \times 10^{-4}$ m^2/ v-sec.

3) $n_i = \frac{1}{\rho e \mu_h (c+1)} = \frac{1}{1.73 \times 10^{-2} \times 1.6 \times 10^{-19} \times 2.93 \times 10^{-4} \times 2.5}$ [Where $c = 1.5$ assumed

$= 4.94 \times 10^{-23}$ carriers/ m^3

4) $n_e = \frac{n_i^2}{n_h} = \frac{2.45 \times 10^{47}}{1.23 \times 10^{24}} = 2.02 \times 10^{23}$ electrons/ m^3

5) $4.94 \times 10^{23} = 2.5 \times 10^{25} \; e^{-W_g/.05}$ from which

$W_g = 0.05 \times 3.94 = 0.197$ ev.

7.2(ii) LEAD SULPHIDE (As Extrinsic Semi-conductor)

1) $n_h = 1.18 \times \frac{1}{1.6 \times 10^{-19} \times 1.226 \times 10^{-3}} = 6.01 \times 10^{21}$ Holes/ m^3

2) $\mu_h = .85 \times \frac{1.26 \times 10^{-3}}{2.1} = 4.96 \times 10^{-4}$ m^2 / v-sec.

3) $n_i = \frac{1}{2.1 \times 1.6 \times 10^{-19} \times 4.96 \times 10^{-4} \times 1.8}$ where $c = \frac{\mu_e}{\mu_h} = \frac{.0640}{.0800} = 0.8$ (assuming)

$= 3.34 \times 10^{+21}$ carriers / m^3

4) $n_e = \frac{1.12 \times 10^{+43}}{6.01 \times 10^{+21}} = 1.86 \times 10^{21}$ electrons/ m^3

5) $3.34 \times 10^{+21} = 5 \times 10^{+21} \times 5 \times 10^{3} \times e^{-W_g / .05}$ from which

$W_g = 0.441$ ev.

LEAD SULPHIDE (As Intrinsic Semi-conductor)

1) $n_i = 1.18 \dfrac{1}{1.6 \times 10^{-19} \times 1.226 \times 10^{-3}} \times 0.2/1.8 = 5.67 \times 10^{20}$ car./m^3

2) $\mu_h = \dfrac{1}{2.1 \times 1.6 \times 10^{-19} \times 5.67 \times 10^{20} \times 1.8} = 2.92 \times 10^{-3}$ m^2/ v-sec.

3) $5.67 \times 10^{+20} = 5 \times 10^{21} \times 5 \times 10^{13} \times e^{-W_g/.05}$ from which

$W_g = .535$ ev.

4) $\mu = (1 - c)\mu_h = (1 - .8) \times 2.97 \times 10^{-3} = 5.94 \times 10^{-4}$ m^2/v-sec.

which is apparant mobility.

Since R_H is positive, $\mu_h > \mu_e$.

7.2(iii) PYRITE (As Extrinsic Semi-conductor)

1) $n_e = 1.18 \times \dfrac{1}{1.6 \times 10^{-19} \times 1.62 \times 10^{-3}} = 4.56 \times 10^{21}$ electrons/m^3

2) $\mu_e = .85 \times \dfrac{1.62 \times 10^{-3}}{5.1} = 2.7 \times 10^{-4}$ m^2/ v-sec.

3) $n_i = \dfrac{1}{\rho e \mu_e (1 + 1/c)}$ where $c = \dfrac{\mu_e}{\mu_h} = 1.5$ (assumed)

$= \dfrac{1}{5.1 \times 1.6 \times 10^{-19} \times 2.7 \times 10^{-4} \times 1.667} = 2.72 \times 10^{21}$ carriers/ m^3

4) $n_h = n_i^2 / n_e = 7.4 \times 10^{42} / 4.56 \times 10^{21} = 1.62 \times 10^{21}$ holes/m^3

5) $2.72 \times 10^{21} = 5 \times 10^{21} \times 5 \times 10^{3} \times e^{-W_g / .05}$ from which

$W_g = 9.456$ ev

Since R_H is positive, μ_h [illegible] μ_e

PYRITE (As Intrinsic Semi-conductor)

1) $n_i = 1.18 \times \frac{1}{1.6 \times 10^{-19} \times 1.62 \times 10^{-3}} \times 0.5/2.5 = 0.91 \times 10^{21}$ carriers/m^3

2) $\mu_e = \frac{1}{\rho e n_i (1 + 1/c)} = \frac{1}{5.1 \times 1.6 \times 10^{-19} \times .91 \times 10^{21} \times 1.667}$

$= 8.1 \times 10^{-4}$ m^2/ v-sec.

3) $.91 \times 10^{21} = 2.5 \times 10^{25} \times e^{-W_g / .05}$ from which

$W_g = 0.51$ ev.

4) Apparant mobility $\mu = (1-c)\mu_e = 0.5 \times 8.1 \times 10^{-4} = 4.05 \times 10^{-4}$ m^2/ v-sec.

Since R_H is negative, μ_h is less than μ_e

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CHAPTER - 8

DISCUSSION OF THE RESULTS

8.1(i) LEAD SULPHIDE

It has been observed from the results that in the case of PbS, $n_h \cong n_e$ (since $n_h = 6.01 \times 10^{21}$ holes/ m^3 and $n_e = 1.86 \times 10^{21}$ electrons/m^3) signifying that the specimen is intrinsic. Intrinsic specimens have the exact stoichiometric composition. As a result of which the resistivity of those samples is much greater than the excess Pb^- or excess S^+ specimens. Measurement of resistivity shows that the PbS sample has a resistivity of the order of 2.1 ohm- m which is about 10^3 times larger than those obtained by Scanlon, Brebrick and Petritz[15]. This higher resistivity is another proof of intrinsic specimen. Moreover, Scanlon and others used a single crystal of PbS while the author had to use natural PbS ores.

The material has been treated as an intrinsic as well as an extrinsic specimen. The result obtained in the two treatment has not differed much. Scanlon and others showed the Hall co-efficient and resistivity of natural single crystal PbS of the order of $R_H = 4 \times 10^{-5}$ m^3/C and 8×10^{-4} ohm-m, which are many times less than those found by the author from polycrystalline ores. The increased value of Hall voltage as well as the Hall co-efficient may be explained by the higher resistivity of the sample, which itself is responsible for exact stoichiometric composition and imperfection in the crystal growth. From the sign of Hall co-efficient it is presumed that the specimen is p-type and the majority carriers are the holes. When two types of carriers are present, R_H is given by

$$R_H = \frac{3\pi}{8e} \frac{n_h \mu_h^2 - n_e \mu_e^2}{(n_h \mu_h + n_e \mu_e)^2} .$$

If the material is treated as intrinsic , $n_h = n_e = n_i$ so that

$R_H = \frac{3\pi}{8e\, n_i} \frac{\mu_h^2 - \mu_e^2}{(\mu_h + \mu_e)^2}$ Since R_H has been found to be positive μ_h is greater than μ_e which is quite consistent with the value of μ_h and μ_e obtained by Putely[36] . But in gneral $\mu_e > \mu_h$. The reason for the result may be ascribed to the imperfection in the crystal growth. The values of μ_h and μ_e found out by Putely were 0.0800 and 0.0640 m^2/ v-sec. respectively. He also suggested that μ of single crystal is greater than that of polycrystalline specimen by 2 – 3 times. The ratio $\frac{\mu_e}{\mu_h} = \frac{.0640}{.0800}$ obtained by Putely has been used by the author in some of the derivation of the results. Measurement of μ obtained by others[37] showed the value of the order of 0.5×10^{-4} to 50×10^{-4} m^2/ v-sec. The mobility value obtained by the author is within the value obtained by H.Berger & Lothrop[37] and is much lower than those obtained by Putely . The low mobilities may be connected with the higher resistivity of the material, higher value of effective masses of holes and reduction of τ by magnetic field(since $\mu_h = \frac{e\tau_h}{m_h}$)

The intrinsic energy gap obtained by Scanlon from single crystal was about 0.37 ev. and by Putely from sintered specimen was about 1.2 ev. The value obtained by the author is closer to the value obtained by Scanlon. It has been seen during the experiment that the Hall voltage sometimes changed from positive value to negative value at higher crystal current. This happened because of the fact that at higher temperature, due to higher current, the stoichiometric composition of PbS has changed by progressive evaporation from the original stoichiometric excess of S^+ to the excess of Pb^{++} . The speciment might have been thus changed from p-type to n-type . Excess S^+ gives rise to holes as majority carriers and excess Pb^{++} gives rise to excess electrons as majority carriers.

8.1(ii) PYRITE

The results on Pyrite have not been found in any literature and therefore, compared with those of PbS. Similar results have been obtained from Pyrite with the only exception that Pyrite shows negative Hall co-efficient indicating that electrons abethe majority carriers and the mobility of electrons is greater than that of holes. Pyrite is therefore a n-type semi-conductor.

8.1(iii) STIBNITE

Of all the samples Sb_2S_3 shows the minium Hall co-efficient and minimum resistivity. Since the resistivity is minimum the number of free carriers is maximum. This is consistent with the fact that the number of free carriers is maximm if the Hall co-efficient is minimum (since $n = \frac{3\pi}{8} \frac{1}{R_H e}$)

Stibnite shows positive Hall co-efficient indicating that the holes are the majority carriers. Stibnite is , therefore, a p-type semi-conductor. The energy gap of Stibnite found 0.19 ev. is minimum of all the samples. This is also quite consistent with the fact that lower the resistivity, lower the energy gap until it vanishes in the case of metals.

8.2 MAGNETIO RESISTANCE

The electron paths are deflected by the application of magnetic field thereby reducing the mean free path , and hence τ is reduced (since $\lambda = v\tau$) and hence σ decreases (since $\sigma = \frac{ne^2\tau}{m}$) , ρ increases.

No work on the magnetoresistance of any of the semi-conducting ores has been found in any literature. The value $\frac{\Delta\rho}{\rho_0}$ given ,however, by Dunlop[38]

was in the range of 0.1 % to 8.5 % for a magnetic field of 0.1 to 1 web/m^2 in the case of n-type Germanium. The increased magneto resistance has been observed with the increase of magnetic field.

Magneto-resistance in all the samples has been observed. Amongst them Stibnite shows the smallest change in magneto resistance from 0.58 % to 2.54 % while Pyrite shows the highest change from 1.6 % to 6.4 % and the change in PbS is intermediate between 0.47 % to 3 %. It has been also observed that the change of magneto resistance depends upon the direction of magnetic field.

8.3 DISCUSSION IN GENERAL

During the experiment it has been observed that permanent change of resistivity occurs if the specimen is placed in a strong magnetic field for a long peirod. Hall voltage has been found to increase by changing the direction of magnetic field suddenly. This has not happened in a fresh or virgin specimen.

The voltage appearing between the Hall probes is not in general the Hall voltage alone. There are other galvenomagnetic and thermo-magnetic effects[39] (Nernst effect, Rhighi - Leduc effect and Ethinghausen effect) which can produce voltage between Hall probes. In addition , IR drop due to probe mis-alignment is present. All these effects are alliminated by balancing this voltages with the potentiometer before magnetic field is applied. Lead Sulphide and Pyrite of lower resistivity of the order of 10^{-2} to 10^{-3} ohm - m have been available but because of their small size (big size was not available) , their Hall co-efficient has not been found. The following precautions were ,however, necessary for making the measurements.

1) To large current was not allowed except in the case of Stibnite which could give rise to Joule heat and carrier injection might cause erroneous result.

2) Pressure contacts were used and rectifying contacts were reduced to the minimum.

3) The IR drop between the Hall probes could not be reduced to zero by changing the alignment of Hall probes and found thata spurious floating potential pf the order of a few millivolts was observed. This might be due to the rectification action of the pressure contacts.

4) All parts of the experiment including the battery set must be well insulated in order to avoid leakage current which may be as higher as 15 to 30 μA.

As a check against leakage one terminal of a micro- ammeter is connected to any point of the experimental set up and the other terminal connected to the ground. Current will flow if leakage is present.

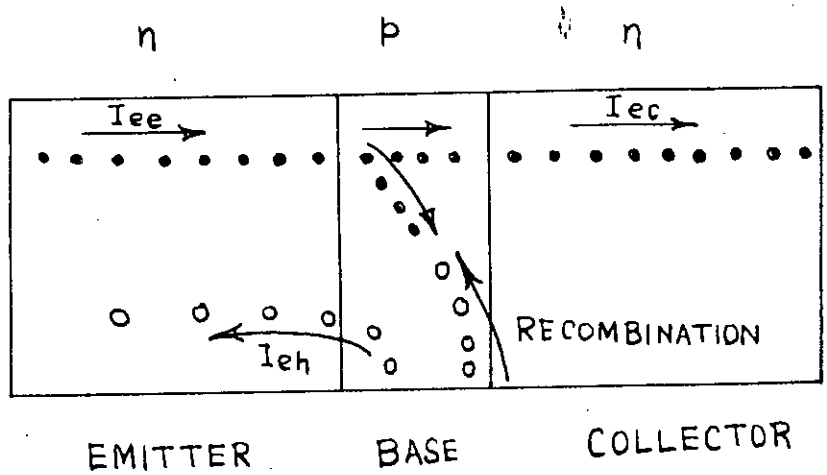
5) Very sensitive galvanometer must be used in order to obtain results of acceptable accuracy.

6) The standard cell and the galvenometer must be protected by a high resistance (at least 10,000 ohm) in series with them.

7) After initial adjustment, the resistance must be shorted by a switch and then final balance should be obhained.

The mobilities and diffusion co-efficients of all the samples are found to possess a value considerably less than that of Germanium or silicon. As mobility and difusion co-efficient play an important part in transistor action, they are considered to be important properties of Semi-conductors.

For good transistor action, nearly all electrons emitted by the emitter should travel through the base and be collected by the collector. But before being collected by the collector, some of these electrons recombine with



SCHEMATIC REPRESENTATION OF THE ELECTRON AND HOLE CURRENTS FLOWING IN AN n-p-n JUNCTION TRANSISTOR.

Fig. 20

holes present in the base. This rate of recombination depends upon difusion length. Diffusion length is a measure of length over which excess of electrons are diffused in the p-type material by the application of forward bias. The density of excess electrons disappears gradually in the p-region because of recombination of electrons with holes(refer fig. 20).

If the diffusion length is appreciable, most of the electrons penetrate into the collector region before recombination takes place as in the case of G_e or S_i signifying their good transistor action.

Pakistani samples, having smaller values of diffusion co-efficients, possess no appreciable diffusion length (since $L \propto \sqrt{D}$) and therefore show no significant transistor action.

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CHAPTER - 9

CONCLUSIONS

9.1 CONCLUSIONS

Pyrite shows the maximum Hall co-efficient while Stibnite shows the minimum Hall co-efficient. The samples of PbS and FeS_2 are found to posses extremely high resistivity (2.1 ohm - m) and (5.1 ohm - m) respectively. These two specimens are therefore, considered to be most likely intrinsic type. Experiments carried out on the samples on the assumption of their extrinsic nature and gave the following results :

Pyrite : $n_e = 4.56 \times 10^{21} / m^3$

$n_h = 1.62 \times 10^{21} / m^3$

Lead Sulphide : $n_h = 6.01 \times 10^{21} / m^3$

$n_e = 1.86 \times 10^{21} / m^3$

However, this assumption did not hold for Stibnite which gave the following results :

Stibnite : $n_h = 1.23 \times 10^{24} / m^3$

$n_e = 2.02 \times 10^{23} / m^3$

The resistivity of Stibnite seemed to ppsses normal value (1.73×10^{-2} ohm -m)

Lead Sulphite and Stibnite show positive Hall co-efficient indicating that the holes are the majority carriers and Pyrite shows negative Hall-co-efficient indicating that electrons are the majority carriers. The former two are, therefore, considered to be p-type Semi-conductors while latter an n-type semi-conductor. The same results had been obtained by ' Thermoelectric Probe Method' in an earlier work carried out by the author[40].

The mobilities and diffusion co-efficients of all the samples had been found to possess a value considerably less than that of Germanium or Silicon. Pakistani samples , having smaller value of diffusion co-efficients, possess no appreciable diffusion length (since $L \propto \sqrt{D}$) and therefore show no signficant transistor action.

The energy gap at room temperature has been evaluated by employing the formula $n_i = 5 \times 10^{21} T^{3/2} e^{-W_g/2kT}$ where n_i = intrinsic carrier concentration. The value of n_i is calculated from $\frac{\sigma}{e\mu_h(1+c)}$ Since the samples are not perfectly intrinsic and maximum resistivity of each sample is not known precisely, the values of n_i and hence the energy gap are of the order of those given in the Table below. The lowest resistivity sample Stibhite is found to have an energy gap = 0.19 ev. and the highest resistivity sample Pyrite = 0.456 ev.

Hall angles at 8.6 Kilogauss for all the samples have been calculated. Magneto-resistance in all the samples has been observed. Lead Sulphide shows the minimum change of resistance with the application of magnetic field and Pyrite, on the other hand, shows the maximum. Number of atoms per cubic meter of the samples has been calculated.

All the above results are tabulated below for the convenience of comparison.

9.2 SUMMARY OF THE EXPERIMENTAL RESULTS

Name of samples.	Stibnite	Lead Sulphide when considered		Pyrite when considered		*41 Germanium
		Extrinsic	Intrinsic	Extrinsic	Intrinsic	
1. Hall coefficient R_H in m^3/C	5.98×10^{-6}	1.226×10^{-3}	1.226×10^{-3}	-1.62×10^{-2}	-1.62×10^{-2}	4.2×10^{-3}
2. Resistivity in ohm-m	1.73×10^{-2}	2.1	2.1	5.1	5.1	10^{-2}
3. Majority carriers	Holes	Holes	Equal holes, electrons	Electrons	Equal holes, electrons	Holes
4. Type of Semi-cond.	p-type	p-type	.....	n-type	....	p-type
5. Maj.carrier concentration/m^3	$1.23 \times 10^{+24}$	6.01×10^{21}	....	4.56×10^{21}	....	3.68×10^{21}
6. Mobility of maj. carriers in $m^2/v\text{-sec.}$	2.935×10^{-4}	4.96×10^{-4}	2.92×10^{-3}	2.7×10^{-4}	8.1×10^{-4}	1.7×10^{-1}
7. Intrinsic carrier concentration/m^3	4.94×10^{23}	3.34×10^{21}	5.67×10^{20}	2.72×10^{21}	0.91×10^{21}	2.5×10^{19}
8. Minority carriers /m^3	2.02×10^{23}	1.86×10^{21}	....	1.62×10^{21}	....	1.7×10^{17}
9. Energy gap at room temp.in ev.	0.197	0.441	0.535	0.4565	0.51	0.75
10. Mag.resistance at 8.6 K.gauss at room tempt in %	2.54	2.55	2.55	6.27	6.27	6.0
11. Hall angle at 8.6 K.gauss	0.0164°	0.0287°	0.0287°	0.0157°	0.0157°	0.36°
12. Diffusion coefficient of maj. carriers, D_h or D_e in $m^2/sec.$	7.62×10^{-6}	1.285×10^{-5}	7.56×10^{-6}	7.0×10^{-6}	2.09×10^{-5}	4.4×10^{-3}
13. No. of atoms /m^3	3.7×10^{28}	3.8×10^{28}	3.8×10^{28}	5×10^{28}	5×10^{28}	4.52×10^{28}

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APPENDIX - I

SOLUTION OF EQUATIONS

APPENDIX - I

1. TO OBTAIN EQUATION (23)

From (i), (ii) & (iii) on page 17, we have,

$$\frac{Z}{e^{(W_c-W_F)/kT}+1} + \frac{Z}{e^{-W_F/kT}+1} = Z$$

Let $x = (W_c - W_F)/kT$ & $y = -W_F/kT$

Hence, $1/(e^x + 1) + 1/(e^y + 1) = 1$

or, $1/(e^x + 1) = e^y/(e^y + 1)$ from

Which, $e^y + 1 = e^{x+y} + e^y$ or, $x+y = 0$

or, $(W_c - 2W_F)/kT = 0$, or, $W_F = W_c/2 = W_g/2$ ...(23)

2. TO OBTAIN EQUATION (25)

$$n_e = 4\pi(2m_e^*/h^2)^{3/2} e^{W_F/kT} \int_{W_g}^{\infty} (W-W_g)^{1/2} e^{-W/kT} dW$$

Let, $x = W - W_g$ or $dx = dW$;

When, $W = \infty$, $x = \infty - W_g = \infty$ .... (i)

When, $W = W_g$, $x = W_g - W_g = 0$ .... (ii)

$$n_e = 4\pi(2m_e^*/h^2)^{3/2} e^{W_F/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-(x+W_g)/kT} dx$$

$$= 4\pi \,,, \quad e^{(W_F - W_g)/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx$$

$$= 4\pi \,,, \,,, \quad \frac{\pi^{\frac{1}{2}}}{2(1/kT)^{3/2}}$$

$$= 2(2\pi m_e^* kT/h^2)^{3/2} e^{(W_F - W_g)/kT} \quad ... \quad (25)$$

3. TO OBTAIN EQUATION (26)

$$n_h = 4\pi (2m_h^*/h^2)^{3/2}\, e^{-W_F/kT} \int_{-\infty}^{0} (-W)^{\frac{1}{2}}\, e^{W/kT}\, dW$$

Let $x = -W$ or, $dx = -dW$;

When $W = 0$, $x = 0$ ... (i)

When $W = -\infty$ $x = \infty$ ... (ii)

$$n_h = -4\pi (2m_h^*/h^2)^{3/2}\, e^{-W_F/kT} \int_{\infty}^{0} e^{-x/kT}\, x^{\frac{1}{2}}\, dx$$

$$= 4\pi \;\; ,, \;\; ,, \int_{0}^{\infty} e^{-x/kT}\, x^{\frac{1}{2}}\, dx$$

$$= 4\pi \;\; ,, \;\; ,, \pi^{\frac{1}{2}} (kT)^{3/2}/2$$

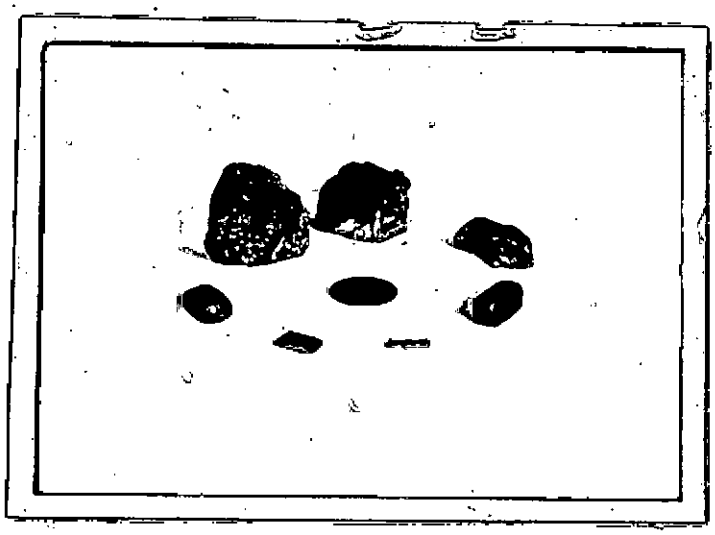
$$= 2 (2\pi m_h^* kT/h^2)^{3/2}\, e^{-W_F/kT} \quad \ldots \quad (26)$$

4. TO OBTAIN EQUATION (27)

$$n_i = 2(2\pi kT\, m/h^2)^{3/2}\, e^{-W_g/2kT}$$

$$= 2\left[\frac{2\pi \times 1.38\times10^{-23}\times9.1\times10^{-31}}{(6.62\times10^{-34})^2}\right] T^{3/2}\, e^{-W_g/2kT}$$

$$= 4.8 \times 10^{21}\, T^{3/2}\, e^{-W_g/2kT} \quad \ldots \quad (27)$$

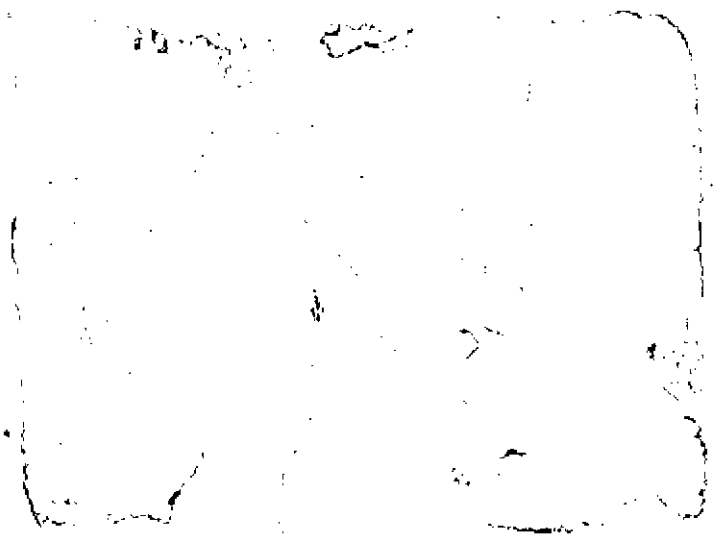


PAKISTANI ORES AND

THEIR SIZED SAMPLES

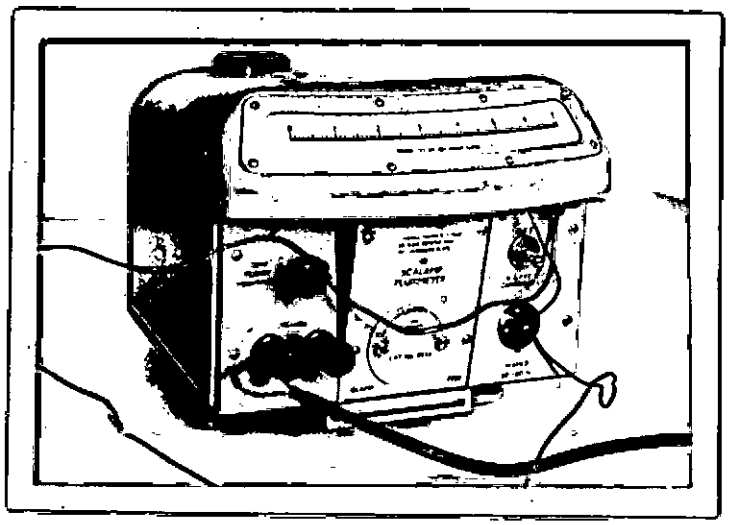
(with one paisa at centre)

PHOTOGRAPH - 2



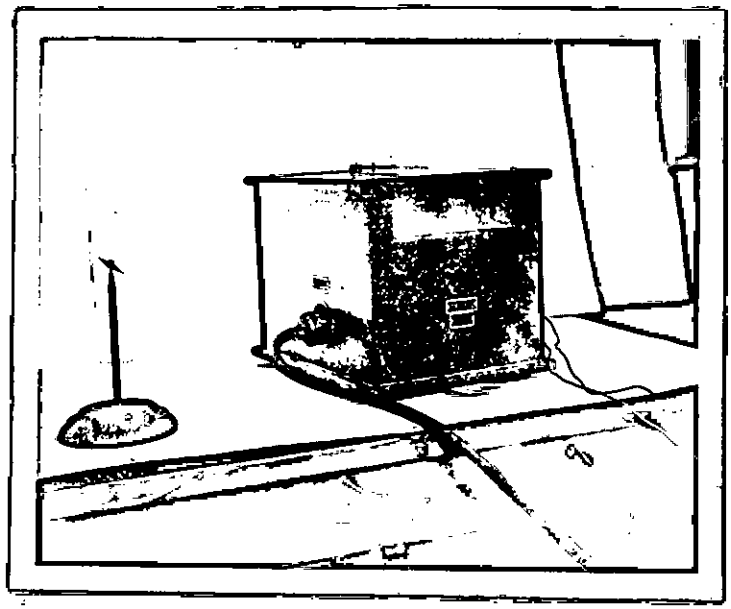
THE SAMPLE HOLDER

PHOTOGRAPH - 3



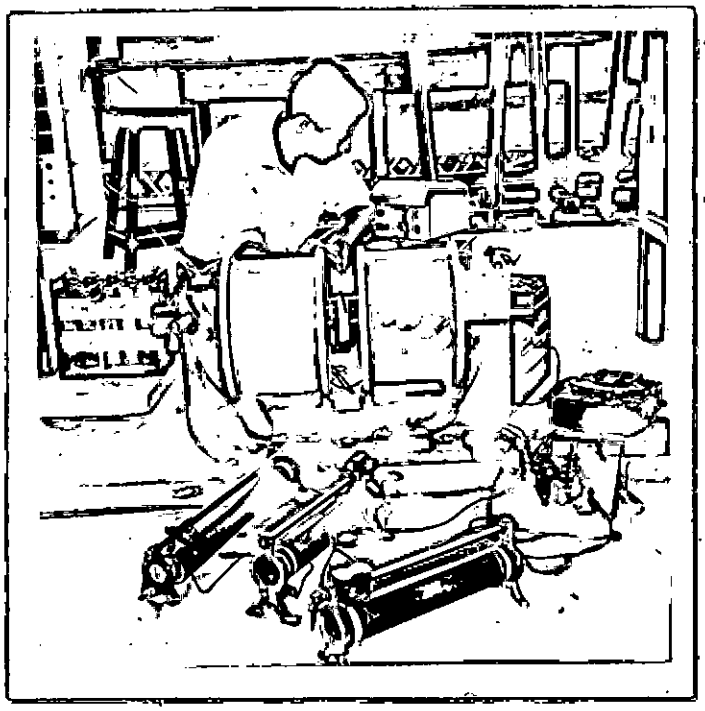
THE FLUXMETER

PHOTOGRAPH - 4



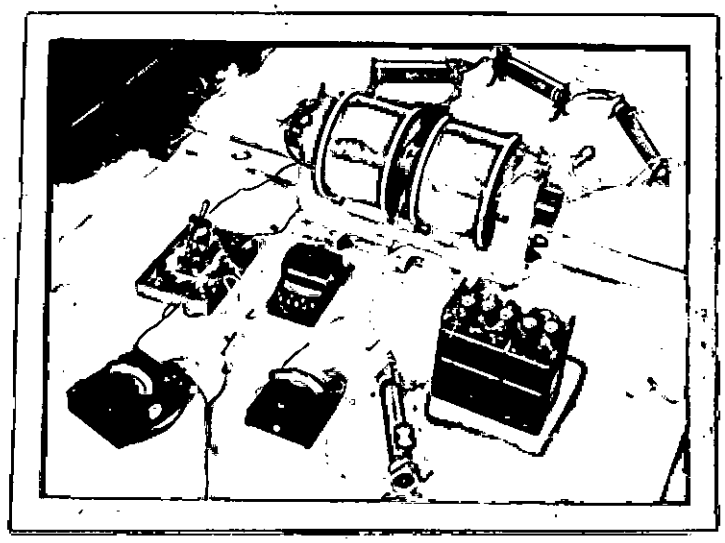
THE GALVANOMETER

PHOTOGRAPH - 5



AN
ARRANGEMENT
FOR
THE CALIBRATION
OF
THE ELECTROMAGNET

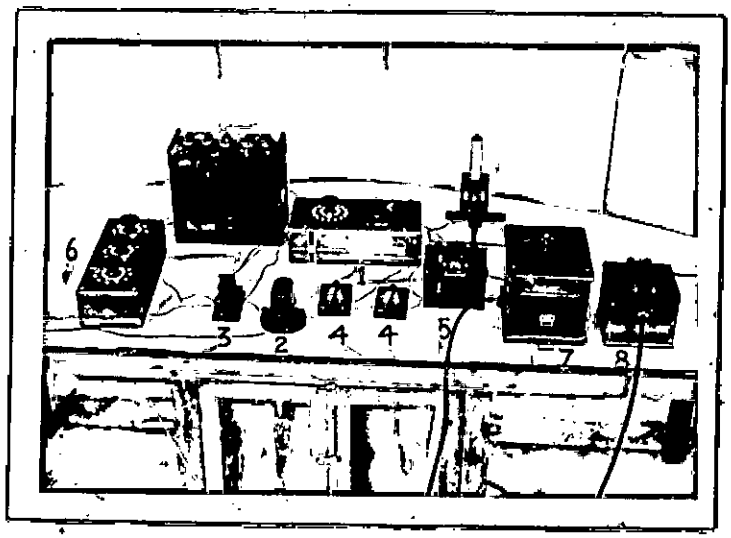
PHOTOGRAPH - 6



AN ARRANGEMENT
FOR
THE PRODUCTION
OF
THE HALL VOLTAGE

PHOTOGRAPH - 7

PHOTOGRAPH - 8



AN EXPERIMENTAL SET-UP FOR THE MEASUREMENT OF THE HALL VOLTAGE.

1. POTENTIOMETER
2. STANDARD CELL
3. D.P.D.T. PIN TYPE SWITCH
4. SINGLE CONTACT KEY (2 REQD.)
5. 10,000 OHM RESISTOR
6. 3-DIAL RESISTANCE BOX 9(1+10+100)
7. GALVANOMETER
8. 4·4 V TRANSFORMER

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THE END

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