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Design and Construction of Hall Effect Gaussmeter*

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ABSTRACT

The paper describes an instrument employing the Hall effect in indium arsenide crystals for measuring magnetic fields from 20 gauss to 25 kilogauss. Various aspects of choosing indium arsenide crystals have been considered. Advantages of this instrument over the conventional fluxmeter have been enumerated. Errors on account of magnetoresistance, temperature variation have also been described.

INTRODUCTION

THE Hall effect was discovered in 1979 by E. H. Hall at the John Hopkins University. It is observed that when a current is passed through the conductor and a magnetic field applied at right angles to the direction of the current flow, a transverse voltage developes and is proportional to the current and the field and inversely proportional to the thickness in the direction of the magnetic field. The proportionality constant is called the Hall coefficient, R.

$$V = \frac{10^{-8} RIH}{t} \quad \ldots(1)$$

where V is in volts, I in amperes, H in gauss, t in cm. and R in cm.^{3}/coulomb. The experimental arrangement for a Hall effect measurement is shown schematically in Fig. 1.

The physical basis for the Hall voltage lies in the fact that the magnetic field causes the carriers to travel in curved paths. This results in piling up of the carriers on the side of the specimen lead and the build up of the Hall voltage in order to counteract the further deviations of the carriers. The schematic representation is shown in Fig. 2. The interpretation of the Hall effect in terms of the carrier concentration is easily seen[2]. In equilibrium the force on carriers on account of the Hall voltage balances the force exerted by the magnetic field and the Hall voltage V is represented as

$$V = \frac{10^{-8} IH}{nqt} \quad \ldots(2)$$

where n is the carrier density and q is the electric charge in coulombs. Comparing with Eq. (1), it follows that

$$R = \frac{1I}{nq} \quad \ldots(3)$$

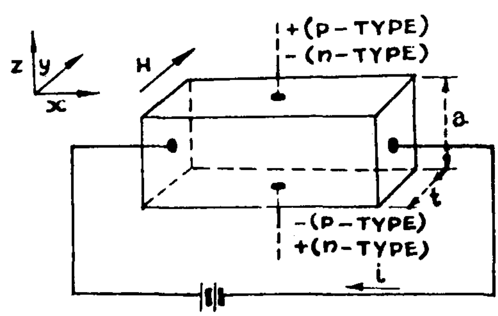

Fig. 1 — Schematic representation of Hall effect measurement

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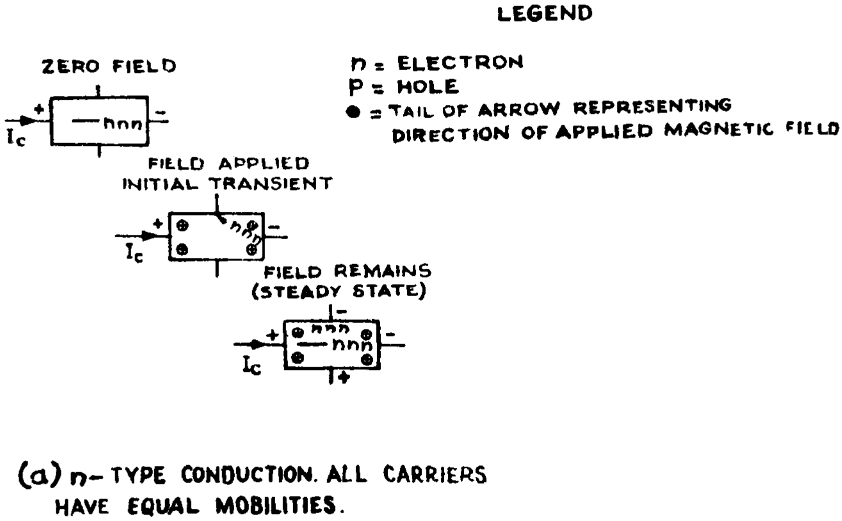

Fig. 2 — Schematic representation of the deviation of carriers

TABLE 1

	Ge N-type	Si N-type	InSb N-type	InAs Intrinsic	Bi $1{\cdot}8\times10^{-3}$
P ohm. cm.	5	4	5×10^{-3}	5×10^{-3}	
R cm.^{3}/coulomb	21,000	7100	380	115	5-10
n/cc.	$3{\cdot}5\times10^{14}$	1×10^{15}	2×10^{16}	$5{\cdot}45\times10^{16}$	6×10^{17}

Table 1 gives the value of R, n for various materials. It is observed that the value of R for metals such as bismuth is very small compared to the semiconductors such as Ge, Si, InSb and InAs. This is on account of the high carrier density and hence low Hall coefficient in metals than in semiconductors. Since the voltages obtainable from available materials were so low, no use outside the laboratory was possible until suitable materials were developed. The development of high mobility semiconductors in recent years has yielded several materials suitable for practical applications of the Hall effect.

CHOICE OF MATERIALS

The Hall effect is basically a majority carrier phenomenon depending upon the bulk material properties of the semiconductor material. Unlike transistors and diodes it is completely independent of surface effects, junction leakage currents and junction threshold voltages. These factors account for the high stability, reproducibility and reliability of the Hall device as compared to other semiconductor devices.

Referring to Eq. (1) it is apparent that to obtain a high output voltage the active element must have a high Hall coefficient, R. Also since the output is proportional to the current density through the element, its resistance should be as low as practical to prevent excessive heating. Since the noise output is essentially thermal low, resistance is also an important requirement for devices to be used at very low levels. Generally the semiconductor materials used for Hall elements are germanium, indium antimonide and indium arsenide. Germanium can be made to exhibit very good temperature characteristics over a narrow temperature range, but high resistance is necessary to obtain reasonable output voltages. Indium antimonide (InSb) has high output and low resistance but the temperature coefficient of the output voltage is about minus 1 per cent per degree C. Indium arsenide (InAs) has somewhat less output than InSb but its temperature coefficient is less than minus 0·1 per cent per degree C. and its resistance low. These considerations make InAs the most suitable material for many Hall device applications. Fig. 3 gives the variation of Hall constant with temperature of InSb and InAs.

Hall device elements may also be made of deposited thin films of InAs and InSb. These elements do not exhibit the same low resistivities and high mobilities as their bulk-material counterparts, hence, they suffer from noise and very low efficiency inherent in high resistance devices. InSb thin film devices may be used in switching type applications where high output voltage is the primary consideration and low noise, good linearity and excellent stability of the bulk material devices is not needed. The advantages of thinner elements are overshadowed by the increase in resistance and decrease in mobility of the thin film devices.

HALL PROBE CONSTRUCTION

Indium arsenide crystals which are generally available in the form of cylindrical ingots of diameter 1·5 cm. are cut into thin slices of 0·5 mm. with a diamond saw. Thinner

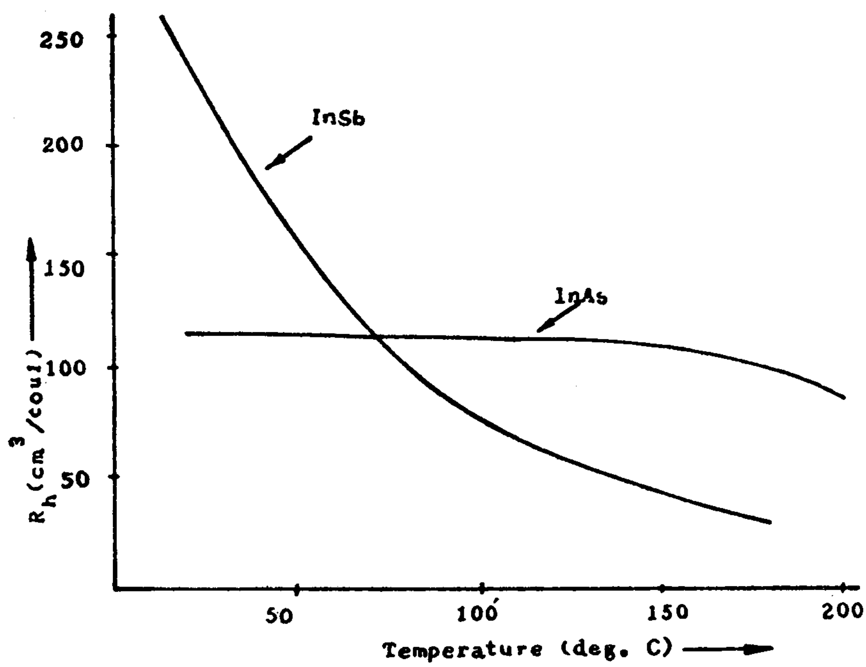

Fig. 3 — Temperature dependence of Hall constant

TABLE 2 — TYPICAL HALL PROBE SPECIFICATIONS

Control current terminal resistance	1·8 ohms
Hall electrode terminal resistance	1·6 ohms
Control current I_c nominal	150 mA.
Magnetic field H, nominal	10 kilogauss
Open circuit sensitivity	150 mV./amp. kg.

TABLE 3 — CALIBRATION POINTS FOR THE RANGE 0-25 KG.

H in kilogauss	Meter reading	H in kilogauss	Meter reading
5·1	5	17·60	17·5
9·95	10	20·200	20·0
12·55	12·5	22·550	22·5
15·30	15·0	25·15	25·0

slices could not be cut as the material is very fragile and little strain on the slice results in the chipping of in it. The slice is further reduced to 0·2 mm. in thickness. This is achieved by carefully lapping the slice on both sides in a slurry of 600 grit silicon carbide powder and water. The slice is now cut in to small pieces of dimensions 5×2 mm. and are thoroughly cleaned in deionized water and nickel plated in the electroless plating solution. The areas where the four contacts are to be made are masked with the wax and the extra plating is removed by etching the Hall plate in a etching solution of hydrofloric, nitric and acetic acid[4]. The wax is then removed by dissolving in trichloroethylene. Four copper wire leads are now attached using indium sloder. A protective coating of araldite is now given to the Hall plate typical characteristics of the Hall probe made in this laboratory are given in Table 2.

ELECTRICAL CIRCUIT

The electrical circuit is described in Fig. 4 and is same as that followed by Pearson[5] excepting that the balancing of the zero magnetic field voltage was achieved by connecting a 1 K. wire wound potentiometer across the control current terminal one and three. The control current is supplied through two 4·5 volts dry cells connected in paralel and resistance R_3 is connected in series to limit the current. R_5 and R_6 are wire-wound potentiometer of value 1 K. and used as trimming resistances for the ranges 5 and 25 kg. respectively. Meter M is a moving coil microammeter with full scale sensitivity of 100 microamps, coil resistance of 40 ohms and an accuracy of 1 per cent of full scale.

CALIBRATION

The probe is placed in a fixed magnetic field of 1 kilogauss and R_3 adjusted to give a full scale meter reading when the range switch is in '1 kg.' position. This correspondes to the passing of 40 mA. of current through the Hall probe. The range switch is then placed back in the 'Calibrate' position and R_2 adjusted to give full scale meter reading corresponding to control current of 40 mA. Trimming resistance R_5 and

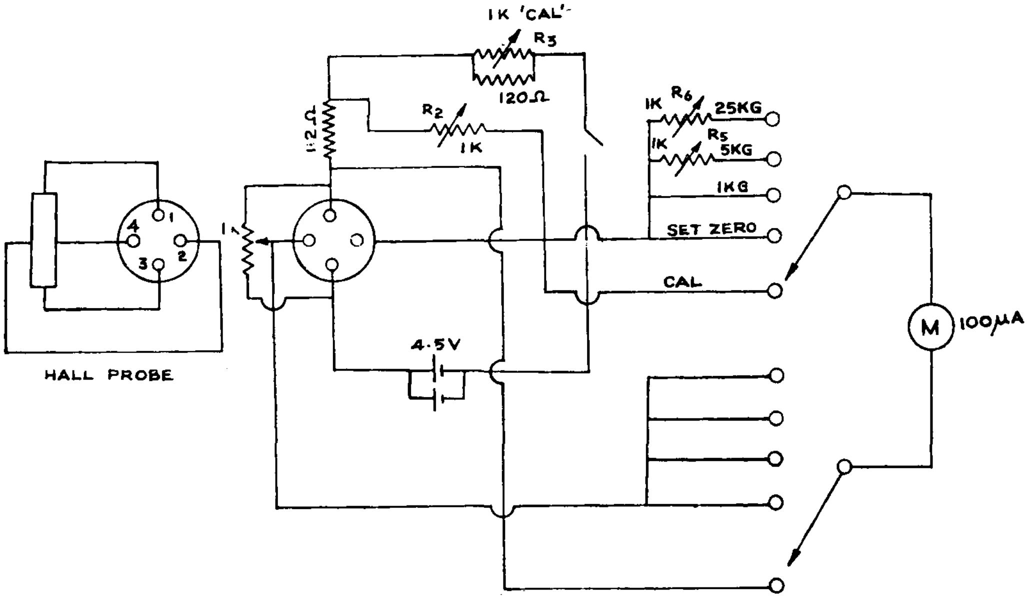

Fig. 4 — Circuit diagram

R_6 are adjusted to give full scale meter reading when the probe is placed in fixed fields of 5 and 25 kilogauss and the range switch on ' 5 and 25 kg. ' positions respectively.

SOURCES OF ERRORS

(i) *Resistive null voltage* — This voltage appears in the absence of the magnetic field because of the misalignment of the Hall terminals. This is reduced to a minimum by carefully connecting the Hall leads while making of the Hall probe and by adjusting R_7 to give a zero meter reading when the probe is outside the magnetic field and the range switch in the ' 1 kg. ' position.

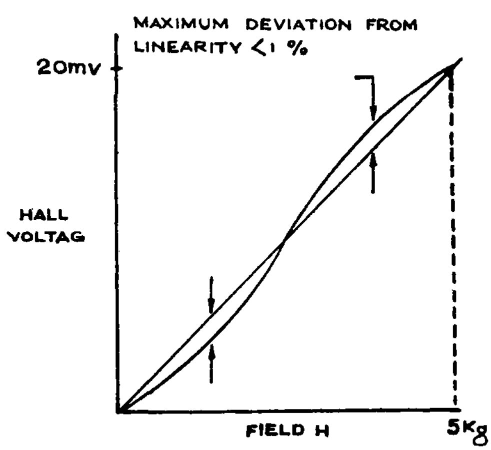

Fig. 5 — Linearity error for range 5 kg.

(ii) *Linearity error* — The Hall voltage as a function of control current I_c and rated field B will vary under different resistive termination and in this case the meter and the trimming resistances. The linearity error is referred to the departure from the straight line as the percent of the maximum or ' full scale ' and is less than 1 per cent (Fig. 4).

(iii) *Temperature dependence* — Conductivity of the semiconductor material generally is a function of the temperature. Since the Hall constant R is inversely proportional to the conductivity, it too depends upon temperature. The mean temperature coefficient of indium arsenide is $-0{\cdot}06$ per cent per degree centrigrade.

(iv) *Magnetoresistance* — At room temperature the conduction in indium arsenide is by only one type of carriers of high mobility and the Hall coefficient and resistivity vary little with the magnetic field. Magnetoresistance has been studied by Weiss and Champness and the result indicates that the ratio of change in resistivity to resistivity in zero magnetic field is proportional to $H^{1 \cdot 65}$, with a resistance increase of 2 per cent at 10 kilogauss. The error on account of the magnetoresistance is reduced to a minimum by suitably choosing the geometry of the specimen with a length to width ratio of 2·5 and with Hall eletrodes one tenth of the element length. A calibration table for the 25 kg. range is provided (Table 6).

APPLICATION

The instrument is useful for the direct reading of steady d.c. fields of 1 kilogauss full scale to 25 kilogauss, full scale with a single probe. It can be also used for studying magnetic properties such as measurement of magnetic permeabilities, saturation flux and leakage paths.

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