HALL GENERATORS

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Abstract
The use of Hall generators is rapidly increasing in electrical engineering as well as in physics experiments. This chapter starts with a brief historical review of these generators followed by the Hall effect theory. Then follows a detailed analysis of Hall-generator parameters and a review of the various applications of these devices.

1. INTRODUCTION

The Hall effect has two important properties: the possibility to measure constant and varying magnetic fields, and the ability to perform multiplication. It is a very powerful tool for the determination of the semiconductor material parameters. The Hall effect has been used for many years in physics, but only after the discovery of the new semiconductor materials have the interesting and useful properties of the Hall generator been used in practical instrumentation and in industry. Recently developed cryogenic Hall generators can be used in superconducting research, magnet testing and sample investigation.

2. GALVANOMAGNETIC PHENOMENA

2.1 Historical review

The Hall effect was discovered by Edwin H. Hall in 1879 at the Johns Hopkins University in Baltimore, USA [1]. The discovery was not made accidentally as is often the case during research on other phenomena. Hall, as a graduate physics student, had been inspired by Maxwell's book on magnetism. In Hall's paper of 1880, he describes the measurements obtained on an iron foil where he found the coefficient (later Hall coefficient) of iron to be about ten times larger than that of gold and silver. In the next year he studied nickel and cobalt. Magnetoresistance (Gauss effect)—increase of resistance of a conductor in a magnetic field—was discovered by W. Thomson in 1856. The first report about the magnetometer using the Hall effect in germanium was made by G.L. Pearson in 1948 [2]. More extensive use of Hall generators was made after 1952 when the technology of InSb production was developed.

2.2 Transport phenomena

Let us imagine a semiconductor material with free electrons, no external fields (electric or magnetic) and no thermal gradients. The electrons collide occasionally with one another and with lattice atoms. They have different velocities and their velocity distribution is determined by the temperature. In the absence of an electrical field the mean velocity of the electrons is zero and no current flows through the semiconductor but when we apply an external field the charged particles are accelerated. The movement of the charged carriers causes charge transport and is therefore called *transport phenomena.* In cases where charge transport is possible, it is due to the *conductivity* of the material. In the next step if we apply the external magnetic field to the semiconductor with internal current density the electric field strength has not in general the same direction as current density. The angle between them is called the *Hall angle*. In semiconductors and metals three types of transport effects can be observed as shown in Table 1.

Table 1

Transport effects in metals and semiconductors

Effect	**Magnetic field**	**Thermal gradients**
Galvanomagnetic	yes	no
Thermoelectric	no	yes
Thermomagnetic	yes	yes

2.3 Magnetoresistance

Magnetoresistance is defined as a change in resistance of a sample produced by an applied magnetic field as illustrated in Fig. 1 (magnetoresistor dependence). Charge carriers drifting in a semiconductor material under the combined action of transverse electric and magnetic vectors are subject to the Lorenz force that deflects the charge carriers and produces the Hall field. If all the charge carriers are identical then the Hall field compensates the Lorentz force, the current lines are invariant with magnetic field, and in consequence the magnetoresistance $\Delta\rho/\rho_o$ is zero. If the charge carriers are not of the same charge type then the Lorentz force is not fully compensated by the Hall field. This produces a current transverse to the electric and magnetic vectors and a change in resistivity of a sample which can be measured along its longitudinal direction of current flow. This is *physical magnetoresistance* while the changes in magnetoresistance caused by changes in shape and dimensions of samples are called *geometrical magnetoresistance* [B1]. Magnetoresitors used this effect, but due to the very high temperature coefficient of the magnetoresistivity and the nonlinear output dependence on the magnetic field they were rarely used for magnetic field measurements.

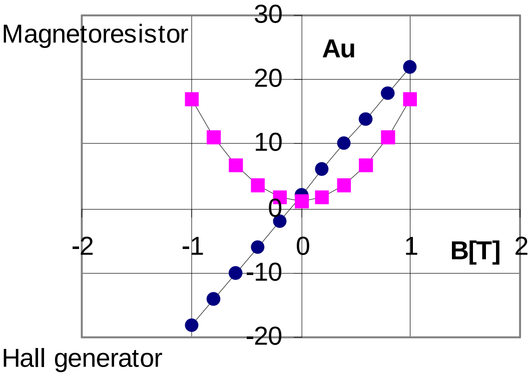

Fig. 1 Basic difference between Hall effect and magnetoresistance

2.4 Hall effect

Electrons, considered as charged particles, drift in the direction of an electrical field $\overline{E}$ with a velocity $\overline{v}$ driven by the force $\overline{F}_e = -e\overline{E}$. In the presence of a transverse magnetic field $\overline{B}$ the drifting electrons are subjected to the Lorentz force $\overline{F}_m = -e(\overline{v} \times \overline{B})$ and some of electrons are deflected in a direction orthogonal to both the electric and magnetic field vectors producing a Hall field which compensates the Lorentz force. The combination of electrically and magnetically-induced forces $\overline{F} = -e(\overline{E} + \overline{v} \times \overline{B})$ acts on the electrons and produces the *Hall effect* [B2]. If the mobility of the electron is defined as:

$$\mu = v/E = (-ev)/F_e \quad (1)$$

Ohm's law as:

$$J = \sigma E \quad (2)$$

and the material is characterised by conductivity:

$$\sigma = ne\mu \quad (3)$$

then for an homogeneous, isotropic, and rectangular Hall generator infinitely long with point Hall and ohmic contacts not connected to the load, the Hall voltage is equal to:

$$U_H = (R_H IB)/t \quad (4)$$

where the Hall coefficient R_H for electrons is defined by:

$$R_H = -1/(ne) = -\mu/\sigma . \quad (5)$$

For Hall generators with finite dimensions it is necessary to include a geometrical correction factor G:

$$U_H = (R_H IB)\, G(a/b, s/a, B)/t \quad (6)$$

where J is the current density, σ the conductivity, n the concentration of electrons, I the Hall generator control current, t the thickness of the active area, a,b the Hall generator dimensions.

2.5 Parasitic effects

The Hall generator current density is distributed inhomogeneously due to the presence of a magnetic field and local inhomogeneities in the semiconductor. Localised Joule heating produces large thermal gradients and these in turn can affect the properties and behaviour of the Hall generators. The Hall generator contacts (contacts between semiconductor and metal) can be regarded as thermocouple junctions which produce thermoelectric voltages. Parasitic effects from the point of view of the Hall generator are thermoelectric and thermomagnetic effects. These effects occur at the same time as a Hall effect and can increase measurement errors.

Seebeck effect. This causes the generation of thermoelectric voltage. If a semiconductor plate with metallic electrodes is heated inhomogeneously in a longitudinal direction a voltage which is proportional to the temperature difference can be measured between the electrodes.

Peltier effect. This is the reverse of the Seebeck effect—the generation of the thermal flow by the electrical current. Potentials generated by thermomagnetic effects (*Ettinghausen*, *Nernst*, *Righi-Leduc)* are usually negligible in comparison with transverse Hall voltages unless large thermal gradients are present [3]. It is important therefore to reduce such gradients to a minimum. All thermomagnetic effects are proportional to the magnetic induction. Due to this fact great attention must be paid in the measurement of high fields.

3. FABRICATION OF HALL GENERATORS

The Hall generator consists of a thin semiconductor plate of dimensions a x b x t equipped with four contacts (see Fig. 2). The control current is supplied by two current contacts, CC, while Hall contacts, HC, used for measurement of the Hall voltage are placed on the plate sides. The Hall generator is most sensitive to the component of magnetic field perpendicular to the semiconductor plate plane.

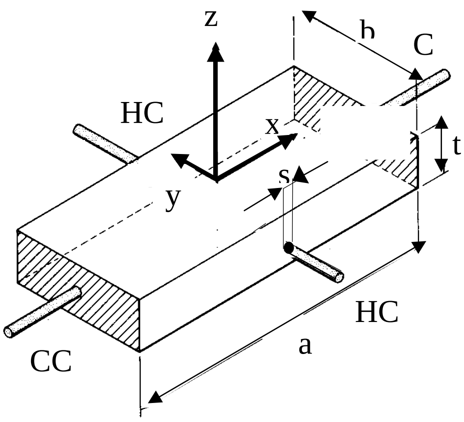

Fig. 2 Rectangular Hall generator.
CC- current contacts,
HC- Hall contacts.

Bulk material Hall generators are prepared by cutting from an ingot [4], followed by abrasion, polishing and etching techniques. The thickness should be reduced to a minimum in order for the Hall voltage to be as large as possible [5]. Semiconductors, in contrast to metals, are extremely brittle and have to be glued to a ceramic substrate which provides mechanical support and protection for the fragile Hall generator.

Thin films prepared by vacuum deposition of intermetallic $A^{III}B^{V}$ compounds on isolating substrates are used for the construction of miniature Hall generators. The semiconductor is formed to the desired shape by photolithography and etching. The electrodes are soldered to copper wires or, for miniature Hall generators, wire bonding is used. Like other semiconductor devices Hall generators must be encapsulated in order to protect them from light, humidity, dust, chemical corrosion and other environmental influences. The package also provides for the electrical connections of the chip with the external circuits. The packages of Hall generators must be non-magnetic and the thermal expansion of the chip and package must also be taken into account, since an inadequate combination of thermal expansion coefficients may lead to an additional offset due to mechanical stress. For high stability measurements unpackaged Hall generators are also viable [6].

3.1 Hall generator materials

In the design and fabrication of Hall generators it is very important to choose the proper material and they are usually prepared from n-type semiconductors where the dominant charge carriers are electrons which have much higher mobilities than holes. The following materials can be used: Ge, Si, InSb, InAs, GaAs, etc [B3-B6]. Germanium, used in earlier years, is not in extensive use nowadays. InSb and InAs are the favoured materials for present day use due to their high mobility. Micron-thin InSb films can be grown from liquid or vapour-phase epitaxy on insulating substrates. Films less than 5 μm in thickness have electron mobilities smaller than those of bulk InSb so that the increase of sensitivity due to decrease of thickness is compensated. Pure InSb has a strong temperature dependence of its electrical parameters because of its small bandgap, Fig. 3, curve a). In order to decrease this temperature dependence donor impurities must be introduced into it, curve c). In comparison with InSb, InAs has a larger bandgap and consequently a reduced temperature dependence of parameters. However its electron mobility is much smaller and it is more difficult to grow in the homogeneous form. The basic material parameters of Hall generator semiconductors are presented in the Table 2.

Table 2

Material properties of semiconductors for Hall generators at 300 K, [B6]

Material	Eg [eV]	n [cm^{-3}]	μ_n [$cm^2V^{-1}s^{-1}$]	$-R_H$[cm^3C^{-1}]
Ge	0.67	$2.4x10^{13}$	$3.9x10^3$	$9x10^4$
Si	1.12	$2.5x10^{15}$	$1.3x10^3$	$2.5x10^3$
InSb	0.17	$9x10^{16}$	$7.0x10^4$	70
InAs	0.36	$5x10^{16}$	$2.2x10^4$	125
GaAs	1.42	$3x10^{15}$	$6.4x10^3$	$2.1x10^3$

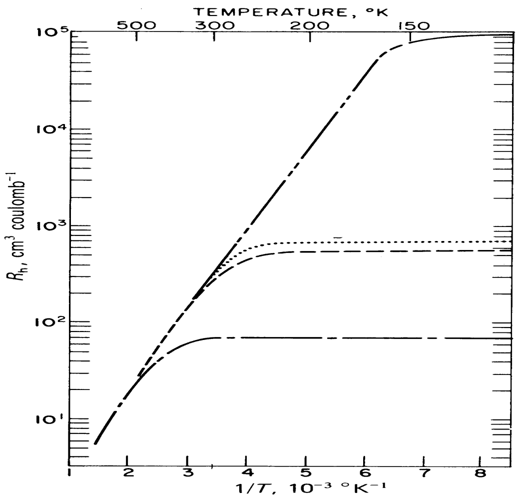

Fig. 3 Temperature dependence of Hall coefficient of n-InSb impurity concentrations: a) -10^{14}, b) -10^{16}, c) -10^{17}, d) -thin film 10^{16} cm^{-3} [B7]

Recent developments in integrated circuit technology has led to the fabrication of super lattices and to the possibility of manufacturing GaAs/AlGaAs and other heterostructures. Such modulation-doped semiconductor layers can be used for the formation of quantum wells with two-dimensional electron gas. The thickness of the device’s active region is less than 10 nm and electron mobility is extremely high 300 000 cm^2 / V.s. These layers can be used for the design of scanning Hall probe microscopes with high spatial resolution, 0.85 μm, and very high magnetic field resolution, 2.9 x 10^{-8} T $Hz^{-1/2}$ at 77 K [B10].

3.2 Hall generator types

Hall generators are developed and produced in a large number of shapes and dimensions depending on their application. From the user point of view the Hall generators (HG) can be divided into several types according to:

- operating temperature
  - cryogenic HG
  - room temperature HG
- magnetic field range
  - low field HG - 02 T
  - high field HG - 240 T etc.

- package
  - transverse HG - measurement in gaps
  - axial HG - measurement in holes
  - unpackaged HG - high stability generator
- active area size
  - normal HG - general purpose
  - microsize HG - inhomogeneous magnetic field measurement
  - number of elements on chip
  - single HG - one element
  - multisystem HG – 215 elements in a line- special
  - tangential HG - measurement of the tangential component of B
  - near to surface HG - measurement of perpendicular component of B very close to the sample surface
  - corner HG - centre of the active area is at the package corner
  - 3 axis HG - measurement of all three perpendicular components of B
  - multisensors - e.g. HG and temperature sensor in one package

This classification was simplified in order to achieve clarity for the reader. The details can be found in [6-8].

4. PARAMETERS OF HALL GENERATOR

4.1 Magnetic field sensitivity

The Hall generator magnetic field sensitivity is one of the most important parameters. This parameter is the ratio of Hall voltage variation to the variation of external magnetic field and all other parameters (such as control current, temperature, pressure, etc.) are constant.

The absolute magnetic field sensitivity S_A is defined as:

$$S_A = |\delta U_H/\delta B| \qquad [V/T] \qquad (7)$$

or

$$S_A = (R_H IG)/t \qquad [V/T] \qquad (8)$$

The relative sensitivity S_R is defined as the ratio of the absolute sensitivity to the Hall generator control current:

$$S_R = S_A/I = (1/I)|\delta U_H/\delta B| \qquad [V/AT] \qquad (9)$$

4.2 Offset voltage

Offset voltage is defined as the output signal from a Hall generator supplied with nominal control current in the absence of a magnetic field, (B = 0).

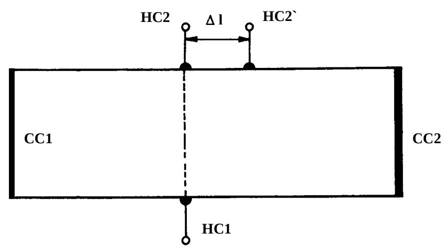

Fig. 4 Geometrical offset Δ l of the Hall contacts with respect to the equipotential line HC1 - HC2

The output voltage of the Hall generator, U_{OUT}, in the presence of a magnetic field is:

$$U_{OUT} = U_H + U_O ,$$

where U_H is the Hall voltage and U_O is the offset voltage. Because the Hall voltage and the offset voltage are combined in the output voltage, the offset cannot be distinguished from the output signal if $B \neq 0$. The offset voltage is, in most cases, small and in the range of µV, and is linearly dependent on I_H up to I_{MAX}. It is temperature dependent and this dependence is usually expressed as a temperature coefficient of the offset voltage. The offset voltage can be caused by several reasons: the Hall electrodes not being placed at the same equipotential line (misalignment voltage), Fig. 4 [B7], or the electrical asymmetry resulting from material inhomogeneities and also from external influences such as light, mechanical stress and variations in temperature.

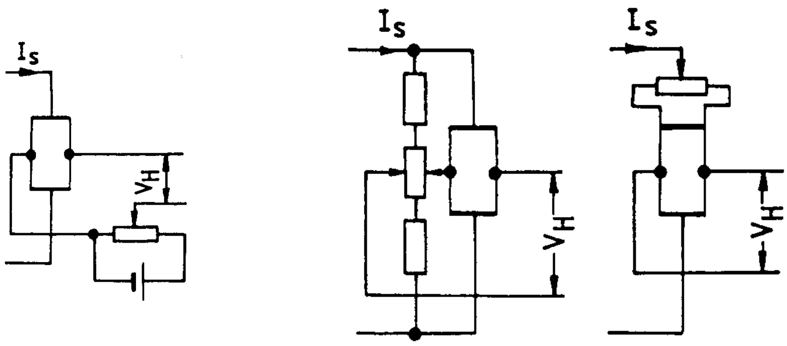

Fig. 5 Hall generator offset-compensation circuits [B7]

The offset voltage can be compensated by means of various external electric circuits, Fig. 5 [B7] but one must keep in mind that no current flow is desirable in the Hall circuit. With each compensation the Hall generator current stability is reduced. However, it appears that a perfect correction of offset voltage cannot be made for all arbitrary control currents, such correction must be made only to those currents usually used in practice.

In the case of AC fields or flying-mode measurements the inductive offset voltage due to small loops in the Hall circuit can be observed. This effect is usually expressed in equivalent area dimensions.

4.3 Temperature dependence of sensitivity

The galvanomagnetic and material parameters of semiconductors used for the fabrication of Hall generators are in general temperature dependent as also are the magnetic field sensitivity, offset voltage, input and output resistances due to their Hall coefficient temperature dependence.

The temperature coefficient of sensitivity γ can be defined as:

$$\gamma = (1/U_H)(\,\delta U_H/\,\delta T) \qquad [K^{-1}] \qquad (10)$$

where δU_H is the difference in Hall voltage caused by temperature change and δT is the value of the temperature change.

The temperature dependence of the offset voltage is defined as:

$$\varepsilon = \delta Uo/\,\delta T \qquad [\mu V/K] \qquad (11)$$

If Hall generators are to have a temperature independent response over a wide temperature range, then they must be made of materials with sufficiently large energy bandgaps so that intrinsically generated carriers represent a negligible fraction of the total carrier density in this temperature region. In materials with small bandgaps the donor impurity density must be high enough to extend the interval where the Hall coefficient is constant, Fig. 3 curve c). However, this procedure leads to a decrease in sensitivity owing to the lower electron mobility produced by ionised impurity scattering [7]. An alternative procedure is to use external circuit elements in conjunction with Hall generators in order to compensate temperature dependence. Loading the output or input terminals of the Hall generator with a thermistor can produce such compensation.

4.4 Linearity error

When using Hall generators in magnetometers it would be very desirable for the relation between Hall voltage and magnetic induction to be linear. Since this is not always the case, it is useful to define the linearity error as in Fig. 6.

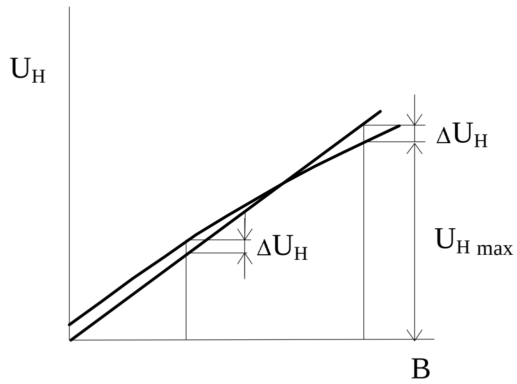

Fig. 6 Linearity error

There are several different definitions of linearity errors:

$$NL = (\Delta U_H/U_H)*100 \qquad [\%] \qquad (12)$$

or

$$NL = (\Delta U_H/U_{Hmax})*100 \qquad [\%] \qquad (13)$$

where NL is the linearity error, ΔU_H is the maximum deviation between the real Hall voltage dependence and the ideal linear Hall voltage dependence on the magnetic field, U_H is the Hall voltage at the point of maximum deviation and U_{Hmax} is the Hall voltage at B_{max}.

The Hall generator exhibits nonlinearity if its sensitivity

(absolute and relative) depends on the magnetic field:

$$NL = (\Delta S/S_0)*100 \qquad [\%] \qquad (14)$$

where ΔS is the deviation from constant sensitivity value S_0 at $B = 0$.

The linearity error consists of two components [10]:

$$NL = NL_M + NL_G \qquad (15)$$

where NL is the total linearity error, NL_M the material non-linearity and NL_G the geometrical non-linearity.

The material and geometrical non-linearities exhibit the same quadratic magnetic field dependence, but with opposite signs. Moreover , the values of non-linearity coefficients are of the same order of magnitude. These facts can be used to design a Hall generator in which the non-linearity effects are compensated or reduced, [10-12]. The geometrical NL may be compensated by loading the Hall output with the appropriate value of loading resistor. The value of the linearity error depends not only on the Hall generator properties and the magnetic field interval employed but also on the type of linearity error definition and approximation criteria for ideal Hall voltage dependence. The measurement errors caused by non-linearities can be reduced by Hall generator calibration and data correction.

4.5 Input and output resistances

Input resistance is the resistance of the current circuit while output resistance is that of the Hall circuit. These are measured at a specified temperature usually (300, 77 or 4.2 K) in the absence of an external magnetic field and with open Hall and input terminals.

The *output resistance* must be as small as possible since the lower is the resistance the lower is the Hall generator output noise. A Hall generator is usually connected to the measuring apparatus by long connecting leads and cables. and it is more advantageous to have low resistance at the end of the cable. Moreover, a low *input resistance* Hall generator can be supplied with a higher control current and therefore higher sensitivity can be obtained. Since the input resistance increases with magnetic field the heating increases with magnetic induction. If the cooling is sufficient the heat generated in the semiconductor can flow out towards both surfaces of the active area.

Electrical excitation is a very important parameter for Hall generator operation. It is usually expressed as a value of nominal control current at which the Hall generator usually works. The control current (0.1 - 100 mA depending on Hall generator type) can be increased up to the specified maximum value. Never do experiments with the control current above the maximum value since the result will be a damaged Hall generator!

4.6 Frequency dependence

The Hall effect is frequency independent up to approximately 1 GHz. It means that the amplitude and the phase of the Hall voltage does not change with frequency as the magnetic induction and/or control current are driven at high frequencies. The frequency dependence of a Hall generator is defined as the amplitude ratio of $U_H(f)/U_H(0)$ to the frequency of the magnetic field. It is mostly influenced by the input and output *circuit parameters*: connection leads, cables, waveguides and *eddy currents* in the semiconductor plate. Eddy currents have a strong frequency dependence. In applications where a Hall generator is placed in an air gap of a magnetic circuit (e.g. multipliers), the frequency response depends on the material parameters of the magnetic circuit and on the width of the air gap.

The equivalent figure of merit is the *response time*. It is defined as the time needed by the output signal to reach a certain percentage (e.g. 98%) of its final value following a step change in the magnetic field or control current. The response time of Hall generators is in the range 10^{-14} to 10^{-8} s [B11].

4.7 Directivity

The magnetic field sensitivity of the Hall generator depends on the angle α between the magnetic field vector and the active area plane $U_H = [(R_H IB)/t]\sin\alpha$. If the B vector is perpendicular to the active surface of the Hall generator, the maximum of the Hall voltage is observed. Any deviation from the angle $\alpha = 90^{\circ}$ reduces the Hall voltage. If the B vector lies in the Hall generator plane in the ideal case the output is zero. If the control current flow is not absolutely parallel to active surface, the vector B parallel to that surface generates an output signal.

Planar Hall effect

Measurement errors can be frequently caused by the fact that the magnetic induction vector is not precisely perpendicular to the Hall generator plane. In this case one component of the magnetic field lies in the Hall generator plane and generates an additional voltage which is added to the Hall voltage. If the angle between *B* and the *x* axis is φ, Fig. 7, then we can obtain the transversal component of electric field:

$$E_y = -\frac{\rho_o \cdot a \cdot B^2 \cdot j_x}{2} \cdot \sin 2\varphi \qquad (16)$$

where *a* is the magnetoresistance coefficient and ρ_o the resistivity without magnetic field

From this expression it is clear that the transversal electric field is equal to B^2 and $\sin 2\varphi$. This means that the error Planar voltage is zero for angles 0, π/2, π, etc. as shown in Fig. 8.

We can use this property when we know the orientation of the component lying in the Hall generator plane. We could rotate the Hall generator so that the direction of control current is parallel or perpendicular to the magnetic field component in the Hall generator plane [14,15]. It is important to note that this error increases with increasing magnetic field. As presented in Fig. 8 the amplitude of the Planar voltage depends on the semiconductor material parameters. It is seen that the material with higher conductivity has a lower amplitude of the Planar voltage. For precise measurement of the magnetic field with unknown orientation it is desirable to use the Hall generator prepared from material with higher conductivity.

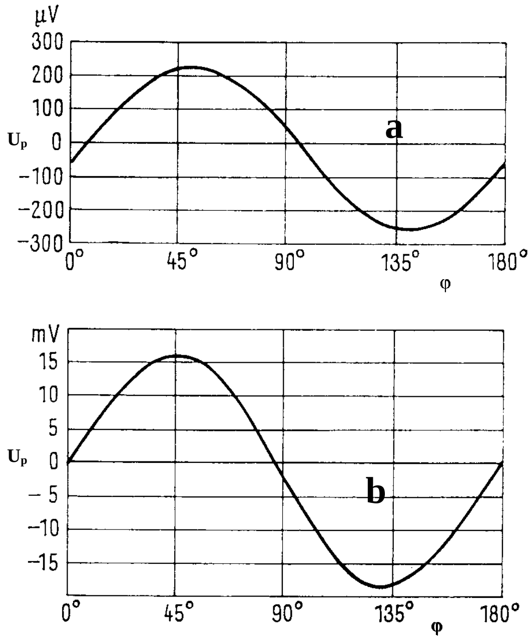

Fig. 8 Planar Hall voltage dependence on the angle between B and I at 1 T. a) n-type InSb, σ = 750 $\Omega^{-1}cm^{-1}$, b) intrinsic InSb, σ = 200 $\Omega^{-1}cm^{-1}$ [B4]

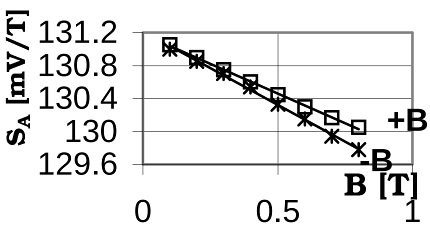

Fig. 9 Hall generator absolute sensitivity dependence on magnetic field

The polarity of a magnetic field can also affect the sensitivity i.e. the sensitivities for +*B* and -*B* are different $U_H(B) \neq -U_H(-B)$, Fig. 9. The differences are in the range of 0.1 - 5%.

5. HALL MAGNETOMETRY

5.1 Calibration and precision

Since the sensitivity of the Hall generator after fabrication is not known, it is necessary to measure the sensitivity at least at one value of the magnetic field or, for high precision measurements, to calibrate it over the whole operational interval of magnetic field. In addition, the Hall generator output voltage is not a linear function of B, therefore a calibration at only two points is not sufficient. From the metrology point of view the calibration consists of comparing the measuring instrument with a common standard of the unit [16, 17]. The magnetic field standard is usually a coil supplied by a known current, the magnetic induction being calculated from the current and coil dimensions. Requirements for the standard coil are:

- high stability of geometrical dimensions
- possibility to measure precisely its dimensions
- high homogeneity of magnetic field in a working space
- free access to a working space
- high accuracy of B data.

The standards are usually the one-layer or Helmholtz coils with a diameter of 250–350 mm wound on a frame made from material with a low, linear, expansion temperature coefficient (e.g. flint, 5.10^{-7} K^{-1}). Another possibility is to use a Cooper or superconducting magnet with measuring equipment capable of measuring the B with a high degree of accuracy. This instrument is based on the NMR method [17] but the flowing-water NMR method can also be used in order to overcome the limitations of the classical NMR method [18, 19].

Since the magnetic field sensitivity of the Hall generator is temperature dependent, for high-precision measurements it is necessary to calibrate the Hall generator at the same temperature at which it will be used in practice. Also the direction of the control current and the polarity of Hall leads must be kept the same, i.e. the Hall generator must work at the same conditions as during calibration. It is very important to reach high accuracy and precision during calibration. These parameters are affected by: homogeneity [20] and stability of the magnetic field, stability of Hall generator current source, stability of the working space temperature, accuracy of the voltmeter used for measurement of the Hall voltage, and also by the accuracy of the NMR apparatus [1921]. During calibration at weak magnetic fields the Earth’s magnetic field and its variations must be taken into consideration.

Precision of the Hall generator measurement is defined as the repeatability of measured data customarily expressed in terms of standard deviation. This means that it is necessary to measure the same data several times under the same conditions. The inherent precision of a Hall generator, under the condition that the magnetic field, temperature and control current are constant, depends upon its noise level (e.g. a Hall generator with a sensitivity S_A = 100 mV/T and a noise voltage $U_N = \pm\ 0.1$ μV has a precision of approximately ± 1 μT).

5.2 Compensation of temperature changes

For high-precision measurements in areas where the temperature might change and where the temperature coefficient is not sufficiently small it is necessary to eliminate the influence of temperature on the Hall generator. This task can be solved in several ways such as:

a) proper *selection of the semiconducting material* it is possible to reduce the temperature coefficient of sensitivity (described in section 4.3)

b) using a *thermostat*. In order to minimise the influence of ambient temperature changes the Hall generator can be placed in a thermostat at constant temperature. For room temperature measurements this temperature should be around 40 °C. The Hall generator is embedded in a split aluminium or copper block to insure uniform temperature distribution. Around the block is wound a heater coil and a temperature sensor is placed in the vicinity of the Hall generator and both are connected to the temperature controller. The complete assembly can be encased in epoxy resin. In this way the Hall generator can be kept at constant temperature to within 0.1 K or better. Great attention must be paid to any additional background magnetic field generated by the heater which must therefore be bifilary-wound. The temperature controller must be proportional, not bistable, in order to avoid transients from switch-on to switch-off of the heater. Unfortunately, this technique results in large overall dimensions of the measuring equipment.

c) *computer correction* with simultaneous measurement of magnetic field and temperature [24]. Knowing the actual temperature, Hall voltage and from calibration tables of the Hall generator at various temperatures, it is possible to calculate the corrected value of the magnetic field. Also, the magnetic field error of the temperature sensor can be eliminated. The measuring method consists of auto-zero and auto-calibration procedures to reduce the thermal drifts of the amplifier and A/D converter. In this way the error of the magnetic field measurement can be reduced from 1 to less than 0.1% in magnetic fields of 00.6 T and a temperature range of 20–60 °C.

5.3 Noise

Hall generator noise is a basic parameter that determines the lowest magnetic field B_{min} detectable by the Hall generator as well as the stability of the output signal. The typical noise spectrum of a Hall generator is shown in Fig. 10 where several different types of noise can be seen [B11]:

- *Low frequency noise* (LF) is caused by the Hall generator temperature variations. Slow temperature fluctuations generate thermovoltages on the Hall contacts which, however, can be eliminated by the use of Hall generator AC control current. In the case of measurement of a DC magnetic field with a Hall generator supplied with DC control current the noise can be reduced by filtering techniques or by an integration voltmeter in which the statistical noise will be averaged to zero. For high-precision measurements it is necessary to keep the Hall generator temperature stable. The fluctuations of the offset voltage are due to the instabilities of the heat exchange between the generator and its surroundings.
- *1/f noise* (1/f) is due to the current flow through the Hall generator. In the generation of this type of noise the surface-to-volume ratio and surface conditions play a dominant role. It shows different behaviours in the presence or absence of a magnetic field.
- *Generation-recombination noise* (G-r) is caused by spontaneous fluctuations in generation and recombination of charge carriers [25]. The fluctuation in charge carrier density causes the noise voltage in the direction parallel and perpendicular to the current flow. Very low levels of this type of noise are due to the short lifetimes of carriers in InSb and InAs.
- *Thermal noise* (T) (Johnson, Nyquist) is generated by the random motion of charge carriers in the Hall generator semiconductive material. The mean square noise voltage $<u^2>$ i.e. the average value of the square of the noise voltage generated by the resistor R_U is:
- $<u^2> = 4kTR_U\Delta f$, where k is the Boltzman constant, T is the absolute temperature, R_U is the Hall generator output resistance and Δf is the bandwidth of the detector.

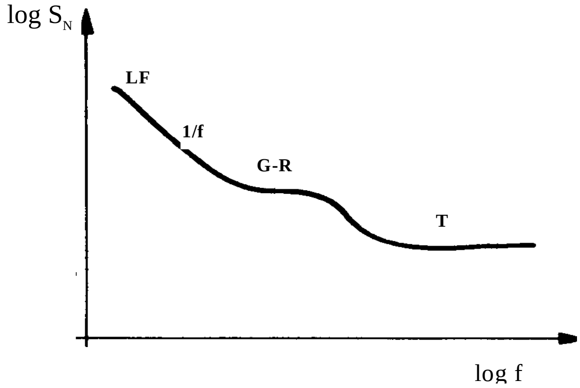

Fig. 10 Typical noise spectrum of a Hall generator:
LF, low frequency,
G-R, generation-recombination,
T,. thermal noise.
[B11]

The magnitude of the measured Hall voltage is also important though its non-linearity and temperature dependence are not significant for many applications and may be compensated by means of external circuits or by numerical corrections. However, accidental fluctuations of the offset voltage and noise cannot be compensated by means of external circuitry.

5.4 Stability and ageing

Hall generator output signal stability depends on noise, stability of offset voltage and stability of magnetic field sensitivity at constant temperature and magnetic field. The output voltage in a magnetic field is made up of the sum of the offset voltage and Hall voltage. Long-term variation of the output voltage may be due to a variation of residual voltage or variation of Hall coefficient. These variations may be caused by a change in geometry of a Hall generator because of corrosion of the surface or electrodes. For stability tests it is necessary to keep the external influences as constant as possible i.e. constant control current, temperature and magnetic field. For the offset voltage testing the Hall generator must be placed in a zero-gauss chamber, to cancel the influence of the earth magnetic field. Evaluation can be made from a large set of measurements (to minimise errors) by statistical analysis. H. Weiss [B4] reported on InAs Hall generator experiments in which he found the mean error of individual measurements to be 1.4×10^{-5}. The offset voltage varied over a period of 8 months by less than the equivalent Hall voltage generated by a magnetic field of 10^{-5} T. At the same time the Hall coefficient remained constant to $\pm 2.10^{-5}$. The ageing process is very important for cryogenic Hall generators because they undergo thermal cycles between 300 K and 4.2 K. InSb generators after 100 thermal cycles change their sensitivity less than $\pm$ 0.04% and the offset voltage change is $< \pm 5$ μV [6]. These changes can be caused by active area material changes (microcracs), changes in contacts, solder, glue, resin, package etc. A first indicator of some of the instabilities is a change of the offset voltage or change in input and output resistances.

6. HALL GENERATOR APPLICATIONS

Hall generators already have innumerable applications and these continually increase. The direct application, measurement of magnetic field, was described in the previous section. The remainder are indirect applications in which the measured quantity is transformed to a magnetic field which is then measured by the generator. These applications result from the independent variables of the output voltage that is dependent on the product of the control current and magnetic field. The magnetic field also has two additional variables—the distance of the magnetic field source from the Hall generator and the angle with respect to the generator plane.

Hall generators can be used to measure current, power, position, number of revolutions and pressure as well as for multiplication of two input signals, for brushless DC motor control, as a contactless switch and applications in the automotive industry. Some of the most interesting applications are described in the following sections.

6.1 Current transducers

Since an electric current is associated with a magnetic field Hall generators are able to detect and measure it so avoiding the need to insert an ammeter into the circuit. This method is especially advantageous for very large values of DC currents since it is not necessary to put a shunt into the circuit. A simple measurement of conductor tangential field is highly linear as non-linear elements such as an iron core are not present.

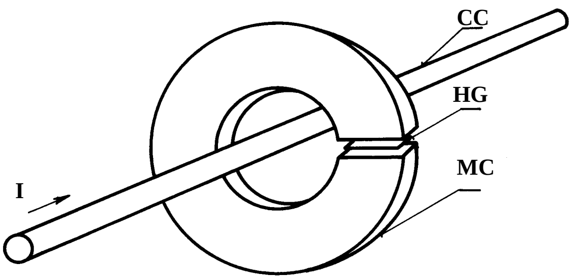

Fig. 11 Current transducer.
HG, Hall generator,
MC, magnetic circuit,
CC, conductor.

In accordance with Ampere's law we have: $\oint Hdl = I$ and $I = 2\pi r U_H/(\mu_o S_A)$, where I is the measured current, U_H the Hall voltage, S_A the Hall generator sensitivity, r its distance from the conductor centre to the Hall generator and μ_o is permeability of free space. This simple method has several limitations. The magnetic field and the signal from the Hall generator are very weak so that background magnetic fields and ferromagnetic objects could cause disturbances to the current measurement. These disadvantages can be overcome, and the sensitivity of measurement can be increased, by using a ferromagnetic core with a Hall generator in its gap Fig. 11. This is the basis for a clip-on ammeter. Using this method currents as high as 400 kA have been measured with an accuracy of 0.52% [B7].

6.2 Contactless signal generation

In this application the Hall generator is used as a receiver for magnetic signals over short distances in order to obtain information about the relative position of two objects—receiver and transmitter. The transmitter is usually a small permanent magnet and the measurement is reduced to detecting the presence or absence of a magnetic field or to detecting the sign of the magnetic field. For this purpose only a very small magnetic induction is required while temperature coefficients have little or no influence on the result. Another advantage is that a permanent magnet requires no energy and therefore no connecting leads are necessary. Furthermore the magnitude of the signal is not dependent on the relative velocity between transmitter and receiver. The output signal is usually processed digitally. Amongst many examples of this application it is important to mention its use in keyboards, end-switches, in the automobile industry and as revolution counters and positioners (Fig. 12). The latter consist of permanent magnets with alternating polarity placed on a disc of non-magnetic material fastened to the shaft to be measured. In front of the disc is placed a Hall generator, the resulting voltage depending sinusoidally on the angle of rotation of this shaft. This method can be used also for the digital control of angular motion (with many magnets) or simply for counting revolutions (with one permanent magnet).

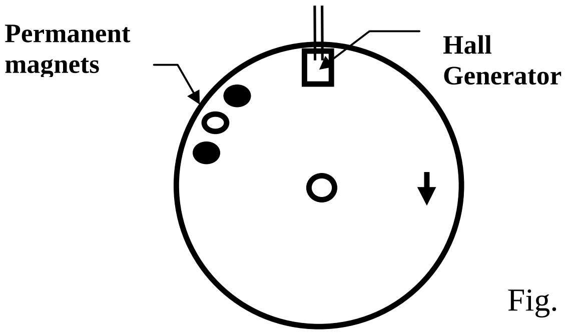

Fig. 12 Digital rotation detector [B4]

6.3 Displacement transducers

Linear displacement transducers depend on measuring along a constant magnetic field gradient with a linear Hall generator. Such transducers can be used as proximity switches.

Angular displacement transducers can be used for the measurement of angles especially where it is important to convert an angle into a voltage without sliding contacts. A circular magnetic circuit is made from ferromagnetic material with four air gaps for Hall generators. A permanent magnet is located at the centre and rotates with the shaft to be measured. Pairs of opposite generators are connected in series in such a way that their output voltages are additive. Transformation of the angles to the analogue signal is purely ohmic up to high frequencies without any distortion. These transducers have the great advantage that they are independent of environmental factors such as dust, smoke and moderate temperature changes.

7. CONCLUSIONS

Future development of Hall generators will take advantage of their high stability, sensitivity and linearity, their low residual voltage, temperature coefficient (of both Hall and residual voltages), input and output resistance and power dissipation as well as their small dimensions. They offer many advantages compared to other sensors: simple measuring arrangement, low cost and the possibility of making continuous measurements. Easy operation and simple electronics make them ideal for many experiments.

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