Understanding Hall Effect Devices

Hall Sensors come in several different packages, allowing measurements both axially and tangentially. Package options include leaded, surface mount, flexible leadstrip, and flip chip configurations.

Hall Effect devices can be used in a variety of applications, sensing a broad spectrum of physical properties. Understanding the operating characteristics of these devices and the tradeoffs made in design decisions will help you achieve the results you're looking for.

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When selecting a Hall Effect device for an application, you must consider several design parameters: the Hall plate material, operating temperature range, sensitivity, temperature performance, packaging, frequency response, cost, and I/O resistance. Recent advances in semiconductor processing have improved various device parameters, but be aware that there are several tradeoffs you must consider during the design phase.

Hall Effect Review

Edwin Herbert Hall discovered the Hall effect in 1879 while working on his doctoral thesis in physics. In 1880, full details of his experimentation were published in *The American Journal of Science* and in *The Philosophical Magazine*.

According to the Hall effect, a particle with charge Q at velocity V, moving within a magnetic field B, will experience the Lorentz force.

$$F = Q\,(V \times B) \qquad (1)$$

The force direction is mutually perpendicular to the directions of the particle velocity and the magnetic field. Under the influence of this force, the electrons pile up on one edge of the conductor. An uneven lateral charge distribution results and gives rise to an electric field (E) that exerts a force.

$$F = QE \qquad (2)$$

opposite in direction to the Lorentz force. At equilibrium, the resultant forces balance (see Figure 1).

Hall Generator Review

A Hall generator consists of a Hall plate made of a semiconductor material, with four leads attached to it. (see figure 2). A constant control current, I_C, flows through two leads, and a differential Hall voltage, V_H, is generated across the other two leads. The Hall voltage is proportional to the product of the input current, I_C, the normal component of the magnetic field B, and the open-circuit (unloaded) product sensitivity constant. (K_{HOC}):

$$V_H = K_{HOC}\, I_C\, B \sin Ø \qquad (3)$$

where:

K_{HOC} = open-circuit product sensitivity (mV/mAkG)

I_C = constant control current (mA)

B = magnitude of the magnetic field density (kG)

Ø = angle in degrees of the incident magnetic field from a line drawn parallel to the Hall plate

Although the Hall effect is present in all conducting materials, it remained a laboratory curiosity until the latter half of the last century. With the advent of semiconductor technology and the development of various III-V compounds, it has become possible to produce Hall voltages several orders of magnitude greater than materials used previously.

Table 1 compares the typical open-circuit product sensitivity constant (K_{HOC}) for commercially available Hall Generators made of bulk indium arsenide (InAs), thin film InAs, gallium arsenide (GaAs), and indium antimonide (InSb). As Table 1 illustrates, product sensitivities span a dynamic range.

The three principle contributing factors are: Hall plate material, Hall plate thickness, and device geometry.

The plate material's physics directly affect product sensitivity. The product sensitivity is proportional to the carrier drift mobility, which is material dependent. Typical electron drift mobilities (in $cm^2\ V^{-1}\ s^{-1}$) are: GaAs = 8.5×10^3, InAs = 2.26×10^4 and InSb = 10^4. Each material also has its own characteristics over temperature. The product sensitivity is also inversely

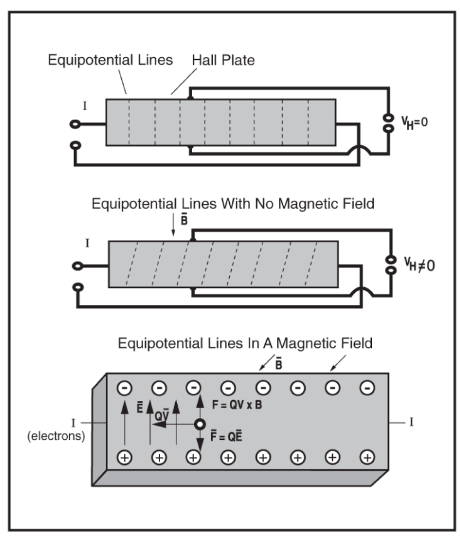

Figure 1. According to the Hall effect, a particle with charge Q at velocity V, moving within a magnetic field B, will experience the Lorentz force, which piles electrons on one side, creating a voltage proportional to the magnetic field.

proportional to the thickness of the Hall plate. The thinner the Hall plate, the higher the product sensitivity. The thickness is determined by the process used to manufacture the device. Bulk devices are slices of ingot material that are lapped and polished. Their thickness is limited by manufacturing methods and handling procedures. The remaining devices may be fabricated using ion implantation, chemical vapor deposition, molecular beam epitaxy, or metal organic chemical vapor deposition. When selecting the thickness of the Hall plate, designers encounter a tradeoff between sensitivity and device resistance – the thinner the plate, the greater the sensitivity and resistance of the device. Typically, designers prefer low I/O resistance because of the low noise, loading concerns, and low voltage drop.

The device geometry also affects product sensitivity. The selection of the geometry involves tradeoffs between product sensitivity, linearity, and device resistance. As the output leads are separated, the sensitivity typically increases and the linearity decreases.

Hall generators are available in a wide range of packages, including (in ascending order of thickness) leaded, flip chip, flex strip, lead frame and surface mount. The component thickness ranges from 0.008 in. to 0.065 in. Leaded devices have four color coded wires of varying lengths attached to the device. The flip chip offers ease of automated assembly and a thin package. The flex strip allows great flexibility in the placement of the device. The lead frame allows through-hole mounting on 0.040 in. or 0.050 in. centers to sense magnetic fields parallel to the plane of the PCB. Surface mount packages allow ease of automated assembly and come in a variety of configurations.

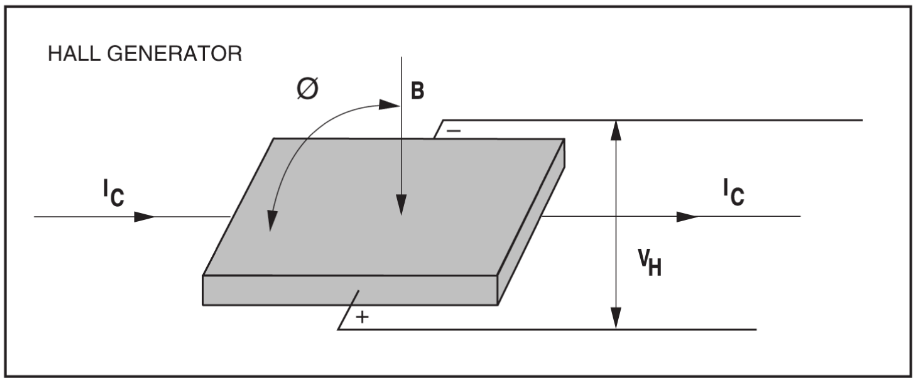

Figure 2. By applying a constant control current on the I_C leads, a differential voltage is generated on the output leads (V_H) proportional to the magnitude of the control current and the magnitude (B) and angle (Ø) of the magnetic field. To maximize the output, the angle of the magnetic field should be perpendicular to the Hall plate.

TABLE 1

Comparison of Typical Product Sensitivity Constants (K_{HOC}) for Commercially Available Hall Generators

Compound	KHOC - Hall Voltage (mV/mAkG)
Bulk InAs	0.10
Thin Film InAs	1.0
GaAs	2.0
InSb	160.0

Hall Generator Operating Characteristics

Nominal Control Current (mA)

A constant current is generally recommended for operating Hall generators because of the dependence of output on the control current and the temperature dependence of the input resistance. For example, if a constant voltage is used, the current flowing through the device will vary as the input resistance changes with temperature, affecting the sensitivity.

Maximum Control Current (mA)

The maximum control current is given at room temperature (T=25°C) and is limited by the power dissipation of the device. The designer typically tends to maximize the control current because doing so increases the output.

I/O Resistance (Ω)

The designer typically wants the resistance to be as low as possible. A low input resistance decreases the voltage drop and reduces power consumption and device self-heating. A low output resistance allows the load resistors to be low, which in turn reduces the overall noise of the design.

Product Sensitivity (mV/mAkG)

This parameter is used to calculate the output voltage for a given field and control current. For example, for a 150 mA control current with a field of 3 kG that is 30° off a perpendicular line from the Hall plate, the output differential voltage, per equation 3, will be:

$$V_H = K_{HOC}\ I_C\ B \sin Ø = (0.10\ \text{mV/mAkG})\ (150\ \text{mA})\ (3\ \text{kG})\ (\sin 60°) = 38.97\ \text{mV} \quad (4)$$

If the magnetic field had been perpendicular to the Hall plate, the angular term would have been sin 90°, which is equal to 1.

It is important to note that V_H is a differential voltage, the difference between the $+V_H$ and $-V_H$ leads. Both leads have a common mode voltage with respect to ground that is equal to the control current times one-half the input resistance. For example, assuming an input resistance of 1.5 Ω and no misalignment voltage:

$$+V_H = -V_H = (0.5)\ I_C\ R_{in} = (0.5)\ (150\ \text{mA})\ (1.5\ \Omega) \quad (5)$$

To calculate the Hall voltage at a given positive field level with respect to ground, simply add one-half the difference voltage to $+V_H$ and subtract the other half from $-V_H$.

$$+V_H = 112.5\,\text{mV} + 19.48\,\text{mV} = 131.98\,\text{mV}$$
$$-V_H = 112.5\,\text{mV} - 19.48\,\text{mV} = 93.02\,\text{mV} \quad (6)$$

For a field in the opposite direction, one-half the difference voltage is subtracted from $+V_H$ and one is added to $-V_H$. This allows you to determine the direction of the magnetic field.

Misalignment Voltage (mV)

The misalignment voltage, V_M, is perhaps better known as an offset voltage. With a zero field, the Hall generator ideally has a zero differential output. However, because of misalignments that occur as a result of process variations, the contacts are not perfectly symmetrical on the Hall plate. The result is an offset. When measuring V_M, it is important to place the Hall generator in a 0 G chamber because the magnetic field of the Earth (~0.5G) will be detected if the device is not shielded. The designer usually includes a potentiometer in the design or nulls the offset using software.

Linearity Termination Resistance (Ω)

The linearity termination resistance is specified to allow the designer to allow the designer to obtain the best linearity from the Hall generator. This is a design tradeoff. As the Hall generator is loaded on the output leads, linearity improves but sensitivity decreases. R_{LIN} loads the Hall generator to obtain the best linearity.

Linearity (%)

This parameter is specified as the deviation from a straight line as a percentage of the reading. A perfect Hall generator would respond identically for both positive and negative magnetic fields.

Reversibility Error (%)

There is a slight error expressed as the reversibility error. For example, if a Hall generator had an output of 30 mV for a positive 2 kG field, it may have a 30.3 mV output for a negative 2 kG field. This error is largely dependent on the difference in contact area and nonuniformity of the Hall plate material.

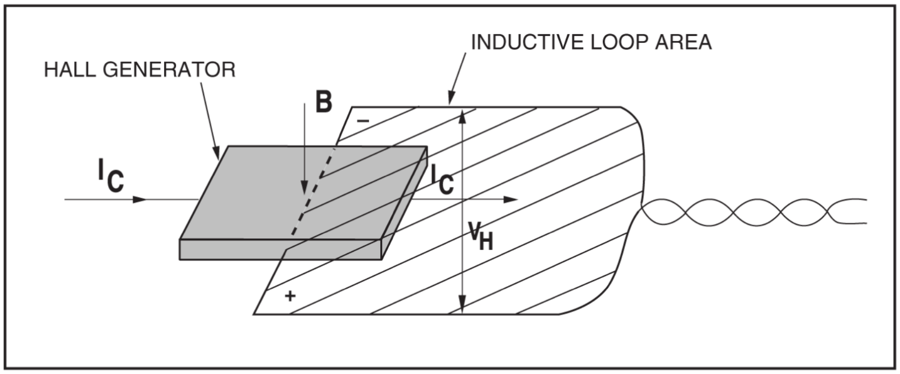

Figure 3. Inherent to all hall sensors is an inductive loop formed by the wires of the Hall plate. For DC magnetic field measurements, this loop has no effect. However, when measuring AC fields, this loop adds an unwanted inducted voltage proportional to the magnitude of the magnetic field, it's rate of change per unit time, and the area encompassed by the loop.

Inductive Area (cm2)

The inductive area should be considered only when designing a generator to measure transient or alternating fields. All Hall generators have an inherent inductive loop area formed by the Hall plate and the corresponding package leads (see Figure 3). Techniques such as twisting the leads and manufacturing the device to minimize the area can be used to minimize the induced voltage. A double-sided Hall plate substrate allows the output and control current leads to be routed so as to overlap each other, essentially eliminating any loop area. This method is expensive and not practical.

Another method involves using a PCB trace to form a loop equal in area but connected in series opposition with the inherent Hall loop. The two induced voltages cancel each other (for further details, see US patent No. 5,416,407). This yields a cost-effective solution. The induced voltage is generated according to Faraday's law of electromagnetic induction, which states that the voltage is negative and proportional to the loop area times the rate of change of the magnetic flux density, B. To calculate the induced voltage:

$$V_{IND} = -A\,(dB/dt)(10^8) \quad (7)$$

where:

V_{IND} = induced voltage (V)
A = area (cm^2)
B = magnetic flux density (G)
t = time (s)

If the Hall generator is placed in a steady-state sinusoidal alternating field, equation 7 is simplified to:

$$V_{IND} = -A\,(2\%)(f)(B)(10^8) \quad (8)$$

where:

V_{IND} = induced voltage (V)
A = area (cm^2)
f = frequency (Hz)
B = the RMS magnetic flux density in gauss.

If the area is unknown, it can be calculated by placing the Hall generator in a sinusoidal magnetic field of known frequency with no control current and measuring the output voltage that is induced. Because the frequency, rms magnitude of the field density, and V_{IND} are known, the area, A, can be calculated.

V_M Drift Over Temperature (µV/°C)

This parameter can have a negative or positive coefficient, making compensation difficult. One method entails supplying the Hall generator with a constant voltage, which reduces the magnitude of the drift.

K_{HOC} Drift Over Temperature (%/°C)

This is the change in sensitivity over temperature. It is always a negative number, driven by the plate material, with a range of –0.01%/°C to -0.08 %/°C for InAs and GaAs and approximately -2%/°C for InSb. The sensitivity drift can be compensated for by designing a constant current source with a positive temperature coefficient. If K_{HOC} is decreasing by 0.05 %/°C, then by injecting a positive 0.05%/°C constant current, V_H is constant over temperature for a constant B field.

Resistance Drift Over Temperature (%/°C)

This parameter is the change in both input and output resistance over temperature. Drift effects on the input resistance can be minimized using a constant current source. A typical resistance drift for InAs and GaAs is +0.3%/°C, and -2%/°C for InSb. Note that a positive resistance drift over temperature compounds the problem of a negative V_{HOC} drift because less current will flow with temperature, which further reduces the output.

One effect not specified in a typical data sheet is the magnetoresistive effect. As a Hall generator is subjected to different magnetic fields, its input and output resistance change. The change is a parabolic effect, with the resistance increasing for both positive and negative fields. For comparative analysis only, a typical change in resistance would be -0.5%/kG for InAs and GaAs and 25%/kG for InSb. As with most other parameters, magnetoresistance is dependent on the Hall plate material and the geometry of the device.

Low fields (<1G) can be measured by placing ferrite concentrators near the Hall generator and packaging the entire assembly. Special packaging allows operation from cryogenic temperatures (-269°C) up to 175°C. Low degradation of device performance when exposed to gamma radiation, and with little or no outgassing in a vacuum allow the use of Hall generators in space. Linear operation to 23 Tesla (1 Tesla = 10 kG) has been verified on certain models. Two and three-axis devices are available for measuring the vector components of magnetic fields.

Typical Applications

Hall generators are used in tachometers, contactless switches, magnetizers, and compasses; for position, tilt/level, pressure, thickness, current, voltage, power, frequency, and magnetic field measurement; for brushless commutation of motors; and by the aviation industry for nondestructive evaluation of materials including detection of hairline cracks in metals.

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