magnetic sensors

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Hall-Effect Magnetic Sensors

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Magnetic field sensors based on the Hall effect are probably the most widely used magnetic sensors. Interestingly, Hall magnetic sensors are relatively rarely used to measure just a magnetic field. They are much more used as a key component in contactless sensors for linear position, angular position, velocity, rotation, and electrical current. From the trend shown in Figure 5.1, we estimate that more than 2 billion Hall magnetic sensors will be sold worldwide in 2000. There is hardly a new car in the world without a dozen Hall magnetic sensors, used mostly as position sensors; millions of ventilators and personal computer disc drives use brushless motors with Hall magnetic sensors inside; and millions of current sensors in various products also depend on Hall magnetic sensors. Moreover, the world production of Hall magnetic sensors is increasing, and the application area is becoming ever broader.

Apart from their simplicity and good characteristics, the importance of Hall magnetic sensors is due to their almost perfect compatibility with microelectronics technology. The optimal material characteristics, device structures and dimensions, and fabrication processes are similar to those readily available in semiconductor industry. Therefore, the development in Hall magnetic sensors does not require much specific investment in fabrication processes, contrary to all other magnetic sensors.

In terms of physical parameters, Hall magnetic sensors usually perform well in the following areas: at magnetic flux densities higher than 1 mT, temperatures between −100°C and +100°C, and frequencies from dc to

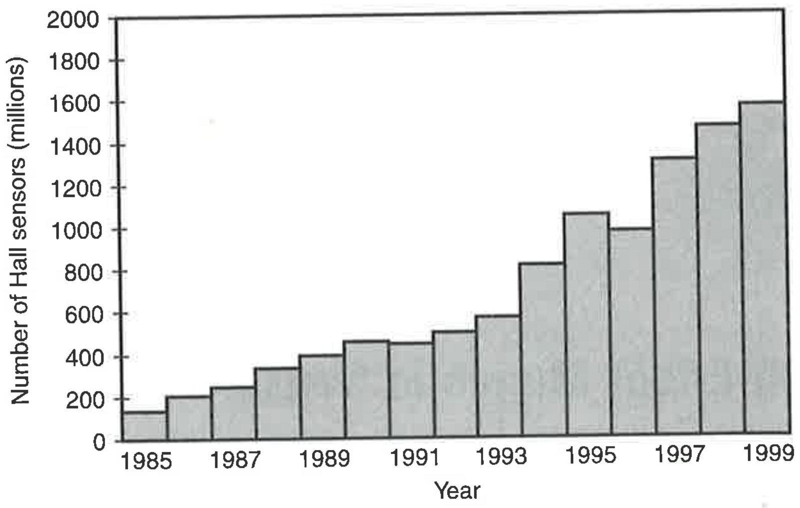

Figure 5.1 World market of Hall sensors.

30 kHz. Of course, the exact values of those parameters depend on the material and the design of the Hall device and may be considerably different in particular cases.

Currently, most applied Hall magnetic sensors are low-cost discrete devices. However, an ever increasing proportion come in the form of integrated circuits. The integration offers an opportunity to apply the system approach to improve the performance in spite of the mediocre characteristics of the basic Hall cells. Moreover, the integrated Hall magnetic sensors are "smart:" they usually incorporate means for biasing, offset reduction, temperature compensation, signal amplification, signal level discrimination, and so on.

A note on the terminology: A basic device exploiting the Hall effect in the form similar to that in which it was discovered is usually called a Hall device, Hall element, or Hall cell. In Japanese literature, the term *Hall element* is used for a discrete Hall device applied as a magnetic sensor. To stress the application of a Hall device, we usually refer to a *Hall magnetic sensor* or just a *Hall sensor*. For magnetic field measurement, a Hall magnetic field sensor, packaged in a suitable case, is normally referred to as a *Hall probe*. In German literature, we often see the expression *Hall generator*, which gives a hint on one aspect of its operation. The term *Hall plate* reflects a conventional form of a Hall device. An integrated circuit, incorporating a combination of a Hall device with some electronic circuitry is usually called an *integrated Hall-effect magnetic sensor* or just a *Hall IC*.

This chapter first briefly discusses some basics of the Hall effect and Hall magnetic sensors (Section 5.1). The three subsequent sections present the three areas of, in our opinion, the highest practical importance in the field: high-mobility discrete Hall plates (Section 5.2), integrated Hall sensors (Section 5.3), and the emerging technology of nonplatelike Hall sensors (Section 5.4).

5.1 Basics of the Hall Effect and Hall Devices

This section is a summary of the physics of Hall magnetic sensors and their basic characteristics. The depth of the explanations are limited to providing just enough of a basis for the following sections. Interested readers can find more detailed treatment of the subject in a monograph on Hall-effect devices [1].

5.1.1 The Hall Effect

The Hall effect is the best known among the physical effects arising in a condensed matter carrying electrical current in the presence of a magnetic field. The effect is named after E. H. Hall, who discovered it in 1879 [2]. A first report on the application of a semiconductor Hall-effect device as a magnetic field sensor was published in 1948 [3].

The Hall effect shows up in its classic and simplest form when a long current-carrying strip is exposed to a dc magnetic field (Figure 5.2). All charge carriers in the strip are then affected by the Lorentz force:

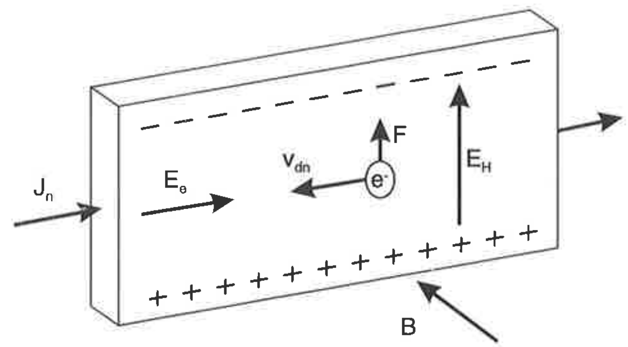

Figure 5.2 The Hall effect in long samples of N-material. The magnetic forces press the electrons toward the upper boundary of the strip so that a Hall voltage appears between the charged edges of the strips.

$$\mathbf{F} = e \cdot \mathbf{E} + e(\mathbf{v} \times \mathbf{B}) \quad (5.1)$$

Here e denotes the electrical charge of a carrier, **E** is the local electrical field, **v** is the velocity of a charge carrier, and **B** is the magnetic flux density, which we take to be perpendicular to the strip plane.

Let us assume that the strip material is a strongly extrinsic N-type semiconductor. We neglect the presence of holes. Along the length of the strip, in the x-direction, an external electrical field E_e is applied. Most of the electrical field **E** in (5.1) is due to that external field. The electrons respond to the external electrical field by moving along the strip with the average drift velocity

$$\mathbf{v}_{dn} = \mu_n \cdot \mathbf{E}_e \quad (5.2)$$

μ_n being the drift mobility of electrons. The associated current density is given by

$$\mathbf{J}_n = q \cdot n \cdot \mu_n \cdot \mathbf{E}_e \quad (5.3)$$

where q is the elementary charge.

The carrier velocity **v** in (5.1) is due to thermal agitation and drift. Let us neglect for a moment the thermal motion. Then the magnetic part of the Lorentz force (5.1) is given by

$$\mathbf{F}_{mn} = q \cdot \mu_n[\mathbf{E}_e \times \mathbf{B}] \quad (5.4)$$

That force pushes the electrons toward the upper edge of the strip. Consequently, the electron concentration at the upper edge of the strip increases and that at the lower edge decreases. Because of those space charges, an electrical field appears between the strip edges. This electrical field, denoted in Figure 5.2 as $\mathbf{E}_H$, acts on the electrons by a force

$$\mathbf{F}_{en} = -q \cdot \mathbf{E}_H \quad (5.5)$$

That force tends to decrease the excess charges at the edges of the strip. At steady state, the two transverse forces $\mathbf{F}_{mn}$ and $\mathbf{F}_{en}$ balance. By equating (5.4) and (5.5), we find

$$\mathbf{E}_H \simeq \mu_n[\mathbf{E}_e \times \mathbf{B}] \quad (5.6)$$

The transverse electric field $\mathbf{E}_H$ is called the Hall electric field. We use the approximate sign because we neglected the thermal agitation of the charge carriers. Nevertheless, (5.6) is a surprisingly close approximation of the accurate result. Without neglecting the thermal agitation of electrons, instead of (5.6) we obtain

$$\mathbf{E}_H = -\mu_{Hn}[\mathbf{E}_e \times \mathbf{B}] \quad (5.7)$$

Here μ_{Hn} denotes the Hall mobility of electrons. The Hall mobility differs a little from the drift mobility: It is given by

$$\mu_{Hn} = r_H \cdot \mu_n \quad (5.8)$$

where r_H is the Hall scattering factor. This is a numerical factor that reflects the influence of the thermal motion of carriers and their scattering on the Hall effect. In most cases, r_H differs less than 20% from unity.

According to (5.6) and (5.7), the Hall electrical field is proportional to the externally applied electrical and magnetic fields. The proportionality coefficient is the carrier mobility. That gives us a first idea about a suitable material to build a magnetic sensor based on the Hall effect: It should be a high-mobility material. Because the mobility of electrons is about three times higher than the mobility of holes, it is better to use an N-type than a P-type semiconductor.

Another useful expression for the Hall electrical field is obtained when the external electrical field in (5.6) is expressed by the current density (5.3):

$$\mathbf{E}_H = -R_H[\mathbf{J} \times \mathbf{B}] \quad (5.9)$$

Here, R_H denotes the Hall coefficient, in this case given by

$$R_H \approx \frac{1}{q \cdot n} \quad (5.10)$$

where n is the density of free electrons.

Here again we use the approximate sign because we neglected the thermal agitation of charge carriers. Without neglecting their thermal agitation, instead of (5.10) we obtain

$$R_H = \frac{r_H}{q \cdot n} \quad (5.11)$$

That gives us another criterion for the choice of the material for a Hall magnetic sensor: it should be a relatively low-doped semiconductor material.

When more than one type of charge carrier is present and/or the material is anisotropic, the Hall coefficient takes a more complicated form. However, if one type of carrier is predominant in terms of the product concentration times mobility, then an equation like (5.11) gives a good approximation for the Hall coefficient.

The most tangible thing associated with the Hall effect is the appearance of a measurable voltage between the edges of the strip. This voltage is known as the Hall voltage. With reference to Figure 5.2, let us choose two points, M and N, at the opposite edges of the strip so that the potential difference between them is zero when $B = 0$. Then the Hall voltage is given by

$$V_H = \int_{S_1}^{S_2} E_H ds \tag{5.12}$$

In this particular case, we find that

$$V_H = \mu_{Hn} \cdot E_e \cdot B \cdot w \tag{5.13}$$

where w denotes the width of the strip. We assume here that the magnetic flux density vector **B** is perpendicular to the strip plane; otherwise, we would have to replace B in (5.13) with the perpendicular component of **B**, which we denote by $B_\perp$.

We can obtain another useful expression for the Hall voltage when we combine (5.3) and (5.13) and take into account that the current density in the strip is given by

$$J = \frac{I}{t \cdot w} \tag{5.14}$$

Here, I denotes the current in the strip and t is the thickness of the strip. So the Hall voltage is also given by

$$V_H = \frac{R_H}{t} \cdot I \cdot B \tag{5.15}$$

which gives us an idea about a suitable geometry of a Hall magnetic sensor: A Hall magnetic sensor usually has the form of a thin plate.

Let us estimate the value of the Hall voltage in a typical Hall sensor application: take $n = 10^{16}$ cm^{-3}, $t = 10$ μm, $I = 1$ mA, and $B_\perp = 100$ mT; then $V_H \sim 60$ mV.

5.1.2 Structure and Geometry of a Hall Device

In accordance with the conclusions drawn in Section 5.1.1, we can imagine the practical Hall magnetic sensor shown in Figure 5.3: a piece of a strip of N-type semiconductor material, fitted with four ohmic contacts at its periphery. The electrical energy is supplied to the device via two of the contacts, called the current contacts (CCs) or the input terminals. The other two contacts are placed at two equi-potential points at the plate boundary. Those two contacts are used to retrieve the Hall voltage. They are called the voltage contacts, the sense contacts (S), or the output terminals. Some early Hall devices really had such a form, with dimensions (length and width) of several millimeters. Most modern Hall magnetic sensors are much smaller, but they still have a general structure reminiscent of that in Figure 5.3. That is why a Hall device is often called a Hall plate.

Apart from the simple rectangular shape shown in Figure 5.3, many other shapes are possible, such as a square, an octagon, or a cross. It could be shown that all these shapes could be transformed into each other by conformal mapping. Therefore, in the ideal case, the basic characteristics of a Hall device are not dependent on its general shape. However, the sensitivity

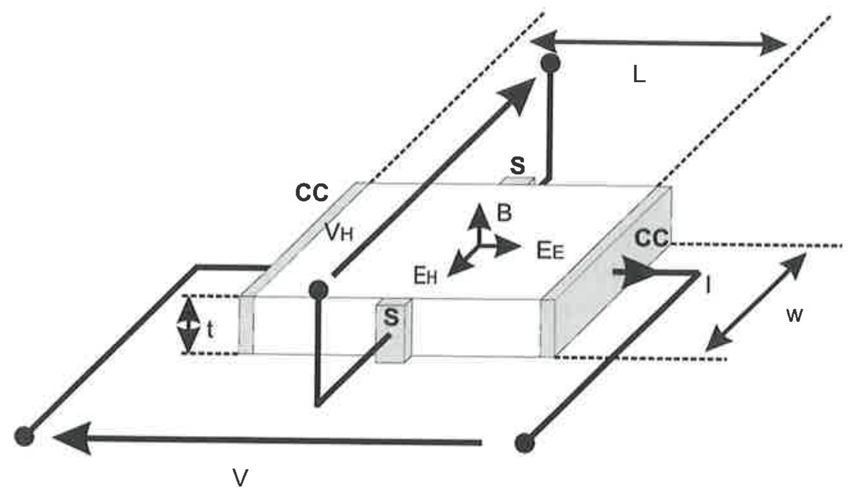

Figure 5.3 Conventional Hall sensor in the shape of a plate.

of a Hall device to parasitic effects, such as fabrication tolerances, may depend a lot on the basic shape of the device. The most commonly used shapes of Hall devices are presented later in this chapter, in the examples of technological realizations of Hall magnetic sensors.

A particularly important issue in the geometry of a Hall device is the relative size of the contacts. If a contact is very small, then the contribution of the semiconductor material resistance adjacent to the contact to the total device resistance may be too high. If an S covers an essential portion of the device periphery, it will short-circuit part of the bias current, and the Hall voltage will be lower than expected. Similarly, if a CC is large, it will short-circuit a part of the Hall voltage.

The influence of the geometry of a Hall plate, including the geometry of the contacts, can be represented by the so-called geometrical correction factor G. That factor describes the diminution of the Hall voltage in a Hall device due to the above-described short-circuiting effects. Let us denote the actually measured Hall voltage by V_H and that of a hypothetical corresponding point-contact Hall device by $V_{H\infty}$. Then the geometrical correction factor is defined as

$$G = \frac{V_H}{V_{H\infty}} \tag{5.16}$$

Theoretically, $0 < G < 1$. In practical Hall devices, we usually find the values of G between 0.7 and 0.9.

Using the notion of G, we can now correct (5.15), which was developed for the case of an infinitely long strip. In a real Hall device, the Hall voltage is given by

$$V_H = G \cdot \frac{R_H}{t} \cdot I \cdot B \tag{5.17}$$

That is probably the most often used equation in the field of Hall magnetic sensors.

5.1.3 Main Characteristics of Hall Magnetic Field Sensors

To be useful as a magnetic sensor, a Hall device must feature a set of characteristics adequate for the intended application. We now discuss a few characteristics that are decisive for the applicability of Hall magnetic sensors [4].

5.1.3.1 Sensitivity

The responsivity of the output voltage of a Hall device to a magnetic field can be characterized by three figures of merit, that is, absolute sensitivity S_A, supply current-related sensitivity S_I, and supply voltage-related sensitivity S_V.

The absolute sensitivity S_A is defined by

$$S_A = \frac{V_H}{B_\perp}, \quad V_H = S_A \cdot B_\perp \tag{5.18}$$

Here V_H is the Hall voltage and $B_\perp$ is the normal (to the Hall plate) component of the magnetic induction.

Supply current-related sensitivity (in short, sensitivity S_I) is defined by

$$S_I = \frac{S_A}{I}, \quad V_H = S_I \cdot I \cdot B_\perp \tag{5.19}$$

where I is the supply (or bias) current of the Hall device. For a strongly extrinsic Hall plate [see (5.17)],

$$S_I = G \cdot \frac{R_H}{t} \tag{5.20}$$

where G denotes the geometrical correction factor ($G \le 1$), R_H is the Hall coefficient, and t is the thickness of the plate.

In most currently used Hall magnetic sensors, one finds the values of the sensitivity S_I of the order of 100 V/AT. It was estimated that a maximum value of the current-related sensitivity of about 3,000 V/AT could be reached in an integrated Hall device [1].

In low-voltage applications, the absolute sensitivity of a Hall magnetic sensor is often limited by the available supply voltage V. The relevant parameter is then the supply voltage-related sensitivity (in short, sensitivity S_V), defined by

$$S_V = \frac{S_A}{V}, \quad V_H = S_V \cdot V \cdot B_\perp \tag{5.21}$$

The value of S_V is particularly important in low-voltage applications of Hall devices.

For a strongly extrinsic Hall plate,

$$S_V = \mu_H \cdot \frac{w}{l} \cdot G \tag{5.22}$$

where μ_H is the Hall mobility of the majority carriers, w/l is the width-to-length ratio of the equivalent rectangle of the Hall plate, and G is the geometry correction factor.

The measured Hall voltage is then given as

$$V_H = \mu_H \cdot \frac{w}{l} \cdot G \cdot V \cdot B_{\perp} \tag{5.23}$$

The value of the term $(w/l) \cdot G$ is the largest in large-contact Hall devices, the limit sensitivity being

$$S_{V\max} = 0.742 \cdot \mu_H \tag{5.24}$$

Sensitivity S_V depends strongly on the material used to fabricate a Hall device. While silicon, with its modest mobility, allows, at room temperature, $S_{V\max} \approx 126$ V/VT, GaAs gives 0.67 V/VT, and InGaAs 0.78 V/VT. Therefore, one clear and important trend in the development of Hall devices is the search for and application of high-mobility materials.

5.1.3.2 Offset

The offset voltage of a Hall device is a quasi-static output voltage that exists in the absence of a magnetic field. With reference to Figure 5.3, in virtue of the symmetry, we would expect the output voltage of the Hall device V_H to be zero in the absence of the magnetic field. However, the symmetry of a Hall device is never perfect: there are always small errors in geometry and variations in doping density, surface conditions, contact resistance, and so forth. Also, a mechanical stress in the Hall device, in combination with piezoresistance effect, can produce an electrical nonsymmetry. The result is a parasitic component in the Hall voltage, which cannot be distinguished from the real quasi-static part of the Hall voltage. Therefore, the offset severely limits the applicability of Hall devices when nonperiodic or low-frequency magnetic signals have to be detected.

The offset of a Hall device is best characterized by the offset-equivalent magnetic induction B_{off}. Using (5.21) and (5.22), we find

$$B_{\text{off}} = \frac{1}{S_V} \cdot \frac{V_{\text{off}}}{V} \approx \frac{1}{\mu_H} \cdot \frac{V_{\text{off}}}{V} \tag{5.25}$$

where we take $(w/l)G \approx 1$. This equation demonstrates once again the importance of a high Hall mobility of the material used for Hall devices.

When microelectronics technology is used to fabricate a Hall device, the offset voltage amounts to usually less than 0.1% of the voltage applied between the input (current) contacts. Inserting this value into (5.25), we find $B_{\text{off}} \approx 10$ mT, 1 mT, 0.1 mT for Si, InGaAs, and InSb Hall devices, respectively.

It is important to note that the offset voltage is not stable. It varies with temperature and time. Even if all other influences are somehow eliminated, there remain long-term (over a period of more than an hour) fluctuations of the output voltage due to $1/f$ noise. In high-quality silicon Hall devices, those fluctuations correspond to a $B_{\text{off}} \approx 10$ μT.

5.1.4 Other Problems

The applicability of Hall magnetic sensors also depends on the following nonideal characteristics.

- Long-term stability of all characteristics, particularly of sensitivity and offset. Long-term instability due to the surface effects and piezoresistive and piezo-Hall effects are fairly well understood. We think that some bulk effects may also play a role, but practically nothing is published in the open literature on the subject. The best published long-term stability of the sensitivity S_I [5] is

$$\frac{\Delta S_I}{S_I} = 10^{-4}/\text{year} \tag{5.26}$$

- Noise. Noise is a limiting factor in low-level magnetic measurements, such as in current sensing. Usually, $1/f$ noise is the most disturbing. If perfect materials and buried structures are used, $1/f$ noise can be decreased by several orders of magnitude. In a good silicon Hall sensor, the noise equivalent magnetic induction in the frequency range from 0.1 Hz to 10 Hz is about 1 μT [5].
- Temperature cross-sensitivity of a Hall device is undesirable sensitivity of its characteristics, such as magnetic sensitivity, to temperature.

In the carrier density saturation range of the semiconductor material used for the Hall device, the temperature cross-sensitivity of the magnetic sensitivity S_I is about 0.1%/K. By a simple compensation, even that can be reduced by a factor of 10. But outside the saturation range, namely, in the intrinsic range and the freeze-out range, the temperature dependence of S_I becomes exponential. That renders a Hall device useless in some applications. To extend the operating range to higher temperatures, wide bandgap semiconductors are used (i.e., GaAs up to 175°C).

5.2 High Electron Mobility Thin-Film Hall Elements

5.2.1 Introduction to Thin-Film Hall Elements

This section describes the fabrication and characteristics in practical and very important thin-film InSb and InAs Hall elements.

Referring to (5.23), the Hall output voltage is proportional to the electron mobility, and so a high-electron mobility material is suitable for fabricating Hall elements. Referring to (5.17), to obtain a Hall element that is highly sensitive to a magnetic field, the active layer must be very thin and have a low carrier density. Therefore, III-V thin-film semiconductors such as InSb, InAs, GaAs, and similar materials have been used for practical Hall elements because they have high electron mobility and their carrier (electron) densities can be easily controlled. Moreover, the thin-film technology is very well suited for fabricating high electron mobility thin films.

The offset voltage V_u between the output electrodes cannot be easily subtracted from the Hall output voltage in practical applications; therefore, reducing the V_u has become the most important problem to be solved in the production of practical Hall elements. The effect can be caused by unwanted asymmetry of the Hall element pattern or electrode and by nonuniformity of material properties of the thin film.

In 1947, Pearson used the Hall effect observed in germanium to measure a magnetic field [3]. That was the first application of the Hall effect for magnetic field sensing. The physical properties of InSb, such as its extremely high electron mobility, were first reported by W. Welker in 1952 [6]. Important progress in InSb thin-film technology for application to Hall effect devices was made by Guenther in 1958 [7, 8]. He proposed the effective vapor pressure control method, referred to as the "three temperatures method," for producing stoichiometric, high electron mobility InSb thin

films by vacuum deposition. In 1960, Sakai and Ohsita also studied Hall effect devices and reported that the vacuum deposition method would be a key technology for the development and mass production of practical, low-cost, highly sensitive Hall elements [9]. Then, in 1975, Asahi Chemical Company developed a highly sensitive InSb thin-film Hall element with a novel device structure and a small plastic package using a novel vacuum deposition method [10, 11]. In 1974, the first design of magnetic field amplification was established. This Hall element has been mass produced and used as a magnetic sensor in the field of consumer electronics [11–13]. Molecular beam epitaxy (MBE) technology was found to be a key technology for growing thin film of III-V compound semiconductors having high electron mobility [14]. By using this technology, it is easy to epitaxially grow high electron mobility single-crystal InAs thin films, or more complex structures such as an InAs quantum well on GaAs single-crystal substrates, which are also used for making Hall elements [15]. The role of MBE in the development of practical Hall element technology will be described later.

5.2.2 Highly Sensitive InSb Hall Elements

This section describes the properties of practical InSb thin-film Hall sensors produced by vacuum deposition. In the early days, InSb Hall elements (Hall plates) were fabricated mainly from thin bulk single-crystal InSb, making them expensive and not suitable for mass production. Under the pressure of a strong demand for low-cost, highly sensitive Hall elements for use in electronic equipment, such as small-sized dc brushless motors, where Hall elements are used mainly as magnetic sensors for fine angular velocity control, highly sensitive InSb thin-film Hall elements with a novel structure and a small plastic package were developed [11–13].

5.2.2.1 Highly Sensitive InSb Hall Elements Produced by Vacuum Deposition

Novel production technology for InSb polycrystal thin films having a high electron mobility of 20,000 to 30,000 cm^2/Vs and a thickness of 0.8 μm grown on thin mica substrates was established by the multisource vacuum deposition method with time-dependent (variable) substrate heating using InSb as a source material. In this unique vacuum deposition method, the crystal stoichiometry is controlled by sequential evaporation of InSb from several source boats. The surface of mica is perfectly flat and stable under heating. By choosing suitable parameters, high electron mobility InSb thin films were obtained. Table 5.1 shows the basic properties of InSb thin films; Figure 5.4 shows the temperature dependence of electron mobility, Hall coefficient, and resistivity.

Table 5.1
Typical Properties of InSb Thin Film Formed by Vacuum Deposition (at 25°C)

	Dopant	Electron Mobility, μ_H	Electron Density, n	Thickness, t
InSb	None	20,000–30,000 cm^2/Vs	$2 \cdot 10^{16}$ cm^{-3}	0.8 μm

The InSb thin films deposited by vacuum deposition on mica substrates showed several new and important properties. The temperature dependence of their Hall coefficients was similar to that of single-crystal InSb. However, the electron mobility showed a very small temperature dependence near room temperature, which was different from single-crystal InSb. In the case of single-crystal InSb, the electron mobility increases at low temperature because of decreasing lattice scattering. InSb thin films grown on mica substrates are polycrystal and have many defects, and the scattering of electrons by crystal boundaries or defects is independent of temperature and does not decrease at low temperature. Moreover, this special electron transport phenomenon leads to a reduction of the electron mobility at low temperature and explains the temperature dependence shown in Figure 5.4(a). That led to the discovery of a new Hall element that had a Hall output voltage with a small temperature dependence, that is, the Hall element enabled us to drive it at constant voltage according to (5.23).

A new device structure of the InSb thin-film Hall element having a high sensitivity was also developed. The InSb thin film was removed from the thin mica substrate and sandwiched between a ferrite substrate and a small ferrite chip. The structure amplified the magnetic field in the gap between the ferrite substrate and chip by a factor of about 3 to 6 compared to the original magnetic field applied to the Hall element. Exact calculation of the amplification factor is complex. Because the InSb thin film in the gap experiences the amplified magnetic field, the Hall elements have ultrahigh sensitivity to the magnetic field. This special structure is shown in Figure 5.5.

Figure 5.6 is a photograph of the Hall element chip.

The standard production process for fabricating these Hall elements is shown in Figure 5.7.

5.2.2.2 Typical Characteristics of Highly Sensitive InSb Hall Elements

Table 5.2 shows typical characteristics (standard specification) of commercial highly sensitive InSb Hall elements [16]. The basic characteristics in a magnetic field (i.e., V_H-B characteristics) are shown in Figure 5.8 [11–13].

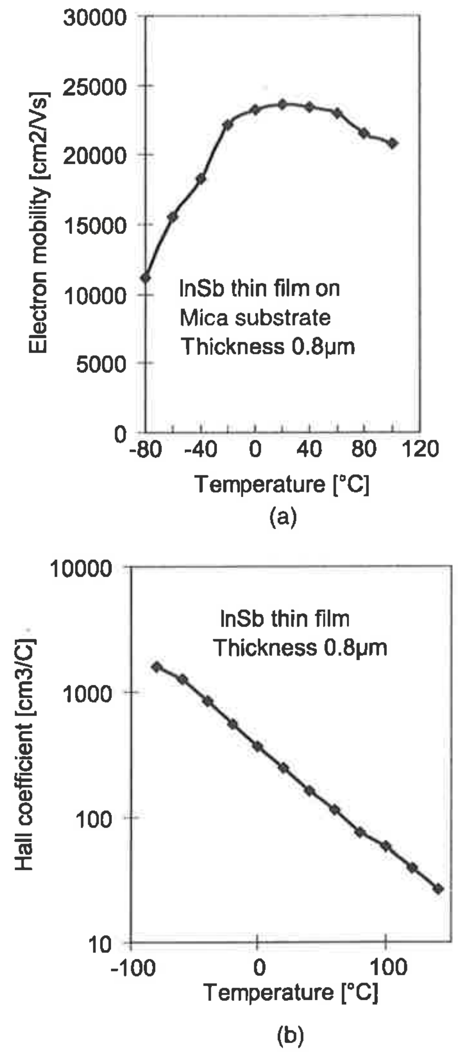

Figure 5.4 Temperature dependence of properties of InSb thin film formed by vacuum deposition (thickness t = 0.8 μm): (a) electron mobility; (b) Hall coefficient; and (c) resistivity.

The temperature dependencies of V_H at constant voltage drive and constant current drive are shown in Figure 5.9(a) and (b), respectively; the temperature dependence of these InSb Hall elements is 2.0%/°C [11–13].

To understand those important temperature characteristics, a brief discussion on the temperature dependence of Hall output voltage near room

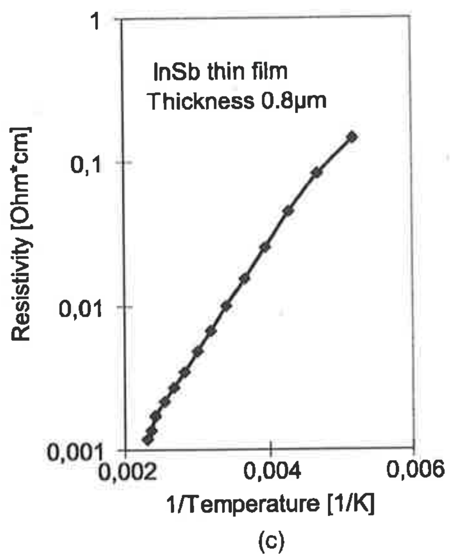

Figure 5.4 (continued).

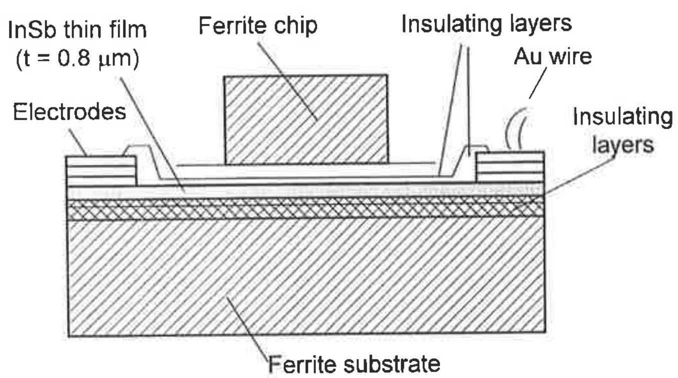

Figure 5.5 The highly sensitive InSb Hall element (cross section).

temperature is important. The temperature coefficient of the Hall output voltage V_H at constant voltage driving is easily derived from (5.13) or (5.23):

$$\frac{1}{V_H} \cdot \frac{dV_H}{dT} = \frac{1}{\mu_H} \cdot \frac{d\mu_H}{dT} \tag{5.27}$$

For constant current driving, it is also derived from (5.11) and (5.15) or (5.17) and expressed as

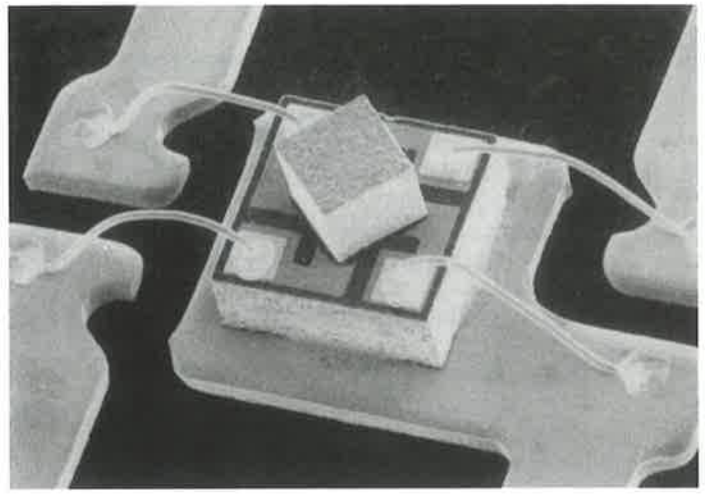

Figure 5.6 Photograph of InSb Hall element chip (Asahi Kasei Electronics: InSb Hall elements HW series).

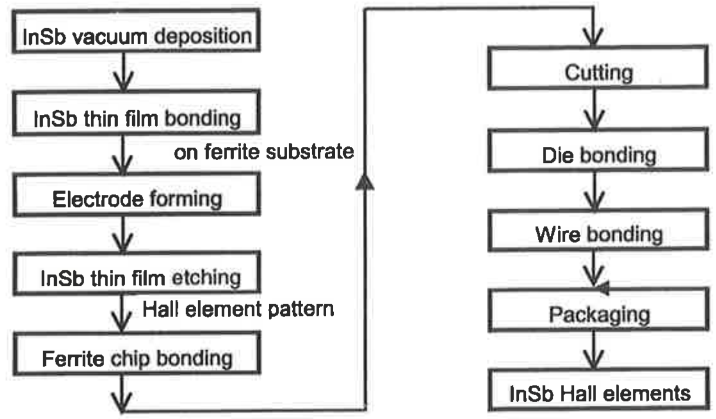

Figure 5.7 Production process of InSb Hall elements.

$$\frac{1}{V_H} \cdot \frac{dV_H}{dT} = -\frac{1}{n} \cdot \frac{dn}{dT} \tag{5.28}$$

Early Hall elements made using single-crystal InSb plates were driven at constant current to avoid breakdown due to excess current because they had a very low input resistance of only a few ohms. Therefore, temperature dependence of V_H is approximately −2%/°C because of the large temperature

Table 5.2
Characteristics of InSb Hall Elements Formed by Vacuum Deposition

(a) Electrical and Magnetic Field Characteristics

	Driving Voltage, V_{in}	Hall Output Voltage, V_H (B = 0.05T)	Offset Voltage, V_{off} (B = 0T)	Resistance, R_{in}
InSb	1V	150–320 mV	<±7 mV	240–550Ω

(b) Absolute Maximum Ratings

Driving Current, I_c	Max. 20 mA
Driving temperature	–40°C to +110°C
Storage temperature	–40°C to +125°C

Source: Asahi Kasei Electronics HW-300A [11–13, 16].

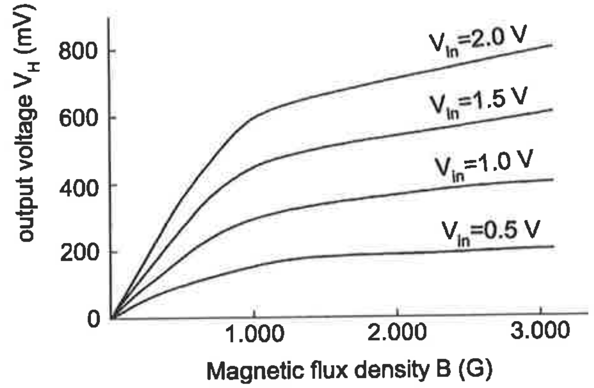

Figure 5.8 Magnetic field characteristics of high-sensitivity thin-film InSb Hall element at constant voltage driving (V_H-B characteristics, Asahi Kasei Electronics HW-300A).

dependence of carrier density n due to the narrow bandgap of InSb. That large temperature dependence was a major problem for applications of Hall elements made from InSb. However, the newly developed thin-film InSb Hall elements have a high input resistance of around 350Ω. Therefore, those Hall elements are stable under an input voltage of 1V to 2V and are driven at a constant voltage. Such constant voltage driving results in the Hall output voltage of highly sensitive InSb Hall elements having a very small or stable

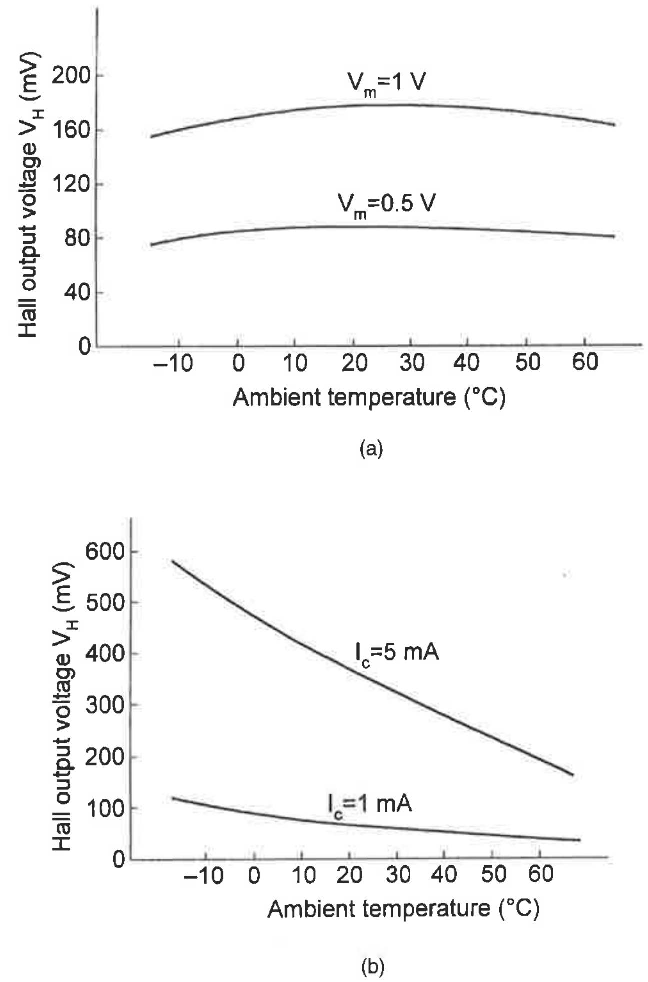

Figure 5.9 Temperature dependence of Hall output voltage at (a) constant voltage driving and (b) constant current driving.

temperature dependence near room temperature. Because the temperature dependence of V_H is the same as electron mobility, as shown in (5.27) and Figure 5.4(b), then this new driving technique reduces the temperature coefficient of the Hall output voltage from –2%/°C to ±0.1%–0.2%/°C near room temperature, as shown in Figure 5.9(a). That is one of the most important practical merits of these highly sensitive InSb thin-film Hall elements produced by the vacuum deposition process and is now a standard driving method for this type of Hall element. These Hall elements have ultrahigh sensitivity to magnetic fields, have practical reliability, and enable the design of small packages that have a wide range of applications.

This InSb Hall element was a commercial success and opened up a new area for brushless dc motor technology and later resulted in the large-scale application of Hall elements as magnetic sensors in small dc brushless motors. The first practical application in 1976 of the highly sensitive Hall element was as a magnetic sensor for music record (audio) player motors. Since then, Hall elements have been mass produced, and recent large-scale applications include dc brushless motors or Hall motors used in VCRs, FDD motors, CD-ROM drive motors of personal computers, and similar electrical equipment. In 1998, more than a billion InSb thin-film Hall elements were produced by vacuum deposition and used in many kinds of applications.

5.2.3 InAs Thin-Film Hall Elements by MBE

The only problem with the InSb Hall elements is their narrow operating temperature range, which is effectively restricted to being near room temperature and which originates from the large temperature coefficient for the input resistance of 2.0%/°C. The success of InSb Hall elements as magnetic sensors has led to many new applications for Hall elements. Some of those new applications impose more severe driving conditions on the Hall elements. A typical new application is automotive sensors, located in the engine compartment or outside the main body frame. This application requires a wide operating temperature range, from –40°C to +150°C; stability over a wide range of driving conditions is also very important. Therefore, a small temperature coefficient of the input resistance of the Hall element or an active layer having a wide bandgap is required. To obtain a Hall element suitable for such new applications, InAs thin-film Hall elements were developed using MBE [15, 17, 18].

Molecular beam epitaxy (MBE) is a technology for growing thin films on single-crystal substrates in an ultrahigh vacuum chamber. With this method, it is possible to fabricate thin films of InAs or III-V compound semiconductor on GaAs substrates (see [14, 15, 17]).

5.2.3.1 Properties of InAs Thin Film for Hall Elements

Bulk single-crystal InAs has a high electron mobility of more than 30,000 cm^2/Vs. The InAs thin films grown by MBE also have a high electron mobility and a bandgap energy of 0.36eV, which is larger than InSb of 0.17eV. Thus, InAs could be used to make a Hall element stable over a wide temperature range because the larger bandgap energy may reduce the temperature instabilities. However, there is a well-known large lattice mismatch between InAs and GaAs (about 7.4%). The fabrication of high-sensitivity Hall elements, using epitaxially grown InAs thin films by liquid phase epitaxy, was previously proposed. Later, by optimizing growth parameters in MBE, a condition was found to grow high-quality InAs thin films, and the large lattice mismatch did not result in any problems in Hall element applications [15, 17, 18].

The room temperature properties of Si doped and undoped InAs thin films grown directly on (100) GaAs substrates (2 degrees off) are shown in Table 5.3.

The temperature characteristics of the InAs thin films are shown in Figure 5.10(a) and (b).

To reduce the temperature dependence of the Hall output voltage for InAs Hall elements at higher temperatures, N-type impurity doping (i.e., Si doping to InAs) was found to be practically effective [15, 17, 20, 21]. However, because this is not trivial, the qualitative discussion that follows shows the effect of doping on the temperature dependence of V_H and input resistance near room temperature.

From (5.28), the temperature dependence of V_H at constant current drive is equal to $-1/n \cdot dn/dT$. Because the dn/dT may be a function of the bandgap energy of InAs, it does not vary much with temperature. Therefore, by doping we can easily increase n and produce a small value of $1/n \cdot dn/dT$. Equation (5.28) illustrates the effectiveness of N-type impurity doping to reduce the temperature dependence of the Hall output voltage at constant current drive. A similar qualitative argument is also valid for the temperature dependence of the resistivity ρ of InAs thin films and input resistance R_{in} of InAs Hall elements. The input resistance of the Hall element in Figure 5.3 is given by

$$R_{in} = \rho \cdot \frac{L}{W \cdot t} \tag{5.29}$$

Table 5.3
Typical Properties of InAs Thin Film Formed by MBE (at 25°C)

	Dopant	Electron Mobility, μ_H	Electron Density, n	Thickness, t
InAs	None	9,000 $cm^2/V \cdot s$	$2.2 \cdot 10^{16}$ cm^{-3}	1.2 μm
InAs	Si	11,000 cm2/V · s	$8 \cdot 10^{16}$ cm^{-3}	0.5 μm

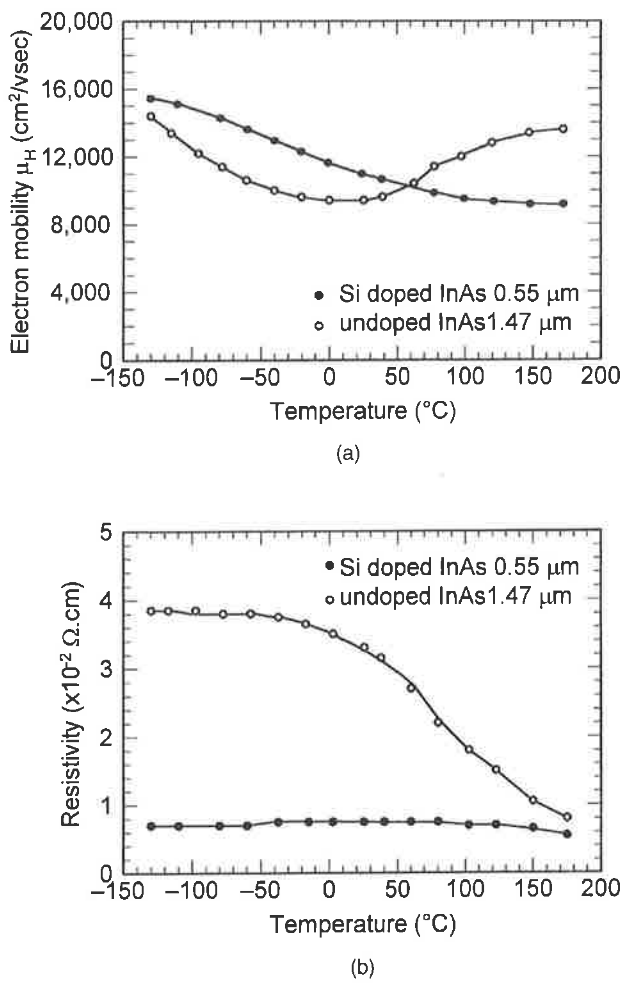

Figure 5.10 Temperature dependence of InAs thin films: (a) electron mobility and (b) resistivity.

Therefore, the temperature coefficient of R_{in} is equal to that of ρ. For a simple model of N-type conduction for the active layer of a Hall element, $\rho = 1/en\mu_H$, where e is the electron charge. Therefore, a simple calculation shows the temperature coefficient of ρ to be given by

$$\frac{1}{\rho} \cdot \frac{d\rho}{dT} = -\frac{1}{n}\frac{dn}{dT} \cdot \frac{1}{\mu_H} \cdot \frac{d\mu_H}{dT} \tag{5.30}$$

That simple result gives us an idea of how to reduce the temperature dependence of the input resistance and V_H of InAs Hall elements. As seen in Figure 5.10(a), the temperature dependence of electron mobility is drastically reduced by Si doping. The reason is the unique electron transport mechanism observed in InAs thin films grown directly on GaAs substrates. Such InAs thin films have a two-layerlike mobility structure in the depth direction. Near the interface region of the InAs layer and GaAs substrate, there is a low mobility layer, and far from the interface region, there is a high electron mobility layer. By Si doping of InAs, electrical conduction is always dominated by the high electron mobility layer without any transition from the low to high electron mobility layer; therefore, the Si-doped InAs thin films show a very small temperature dependence for electron mobility [15, 20]. Thus, the Hall output voltage V_H of Si-doped InAs thin-film Hall elements shows a very small temperature dependence at constant drive voltage, as seen from (5.27) and Figure 5.10(a). Moreover, because both terms on the left side of (5.30) are reduced by doping, there is also a very small temperature dependence for resistivity and thus for input resistance of InAs Hall elements. Therefore, Si-doped InAs thin films are suitable for practical Hall elements. The room temperature electron density and mobility of typical 0.5-μm-thick Si-doped InAs thin films for use in Hall elements are $8 \cdot 10^{16}/\text{cm}^3$ and 11,000 cm^2/Vs, respectively.

5.2.3.2 Design and Fabrication of InAs Hall Elements

InAs thin films doped with Si were used for designing practical InAs Hall elements with 0.36-mm^2 chip size. The InAs thin films were processed to form Hall elements by a specially developed procedure and assembled in a mass production line. The fabrication process is shown in Figure 5.11.

Figure 5.12 is a photograph of an InAs Hall element chip bonded on a lead island.

5.2.3.3 Typical Characteristics of InAs Hall Elements

Table 5.4 lists the standard specifications of InAs Hall elements [15, 16]. The typical Hall output voltage (or sensitivity) of this Hall element in a magnetic field is 100 mV/0.05T/6V. The characteristics are shown in Figure 5.13.

Good linearity of Hall output voltage for sensing a magnetic field is observed. The temperature dependence of the Hall output voltage is shown in Figure 5.14 and that of input resistance in Figure 5.15.

Because the input resistance of the InAs Hall element does not change much with temperature, practical applications over a wide temperature range

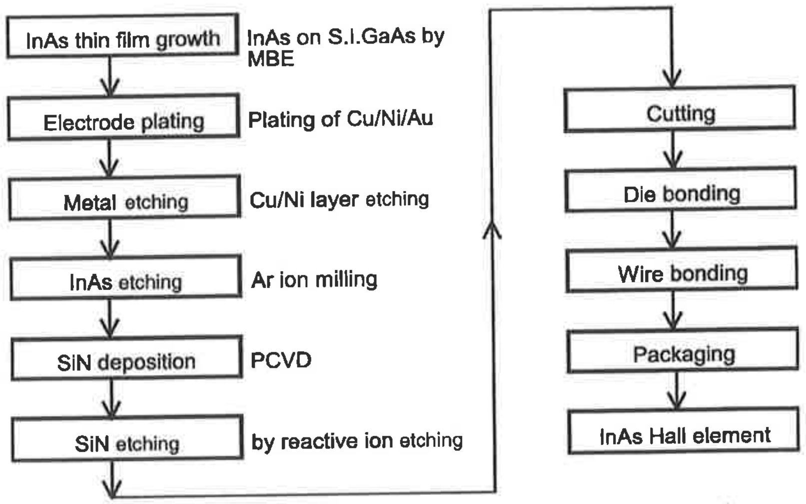

Figure 5.11 Fabrication process of InAs Hall elements.

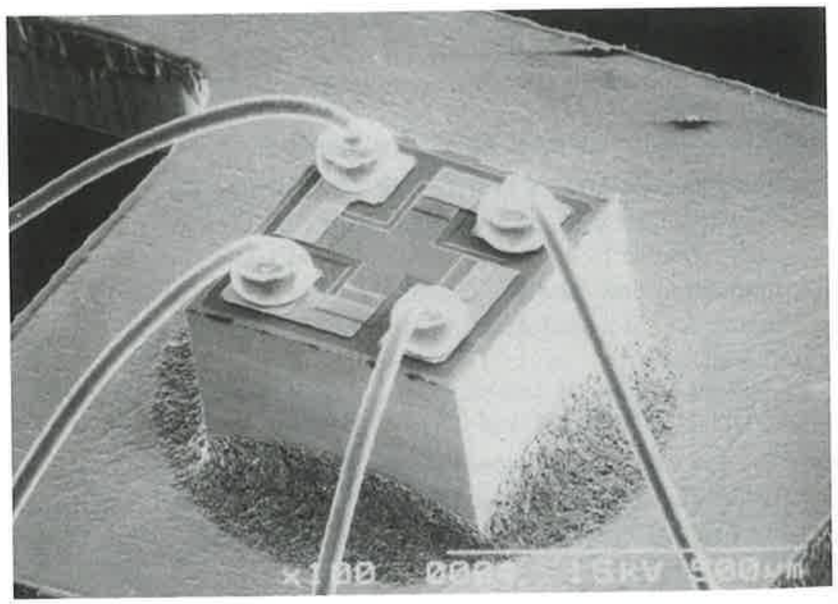

Figure 5.12 Photograph of the InAs Hall element chip.

Table 5.4
Typical Characteristics of Si-Doped InAs Hall Elements Formed by MBE: Electrical and Magnetic Field Characteristics

	Driving Voltage, V_{in}	**Hall Output Voltage, V_H (B = 0.05T)**	**Offset Voltage, V_μ (B = 0T)**	**Resistance, R_{in}**
InAs	6V	100 mV	<±16 mV	400Ω

Source: Asahi Kasei Electronics HZ-302C.

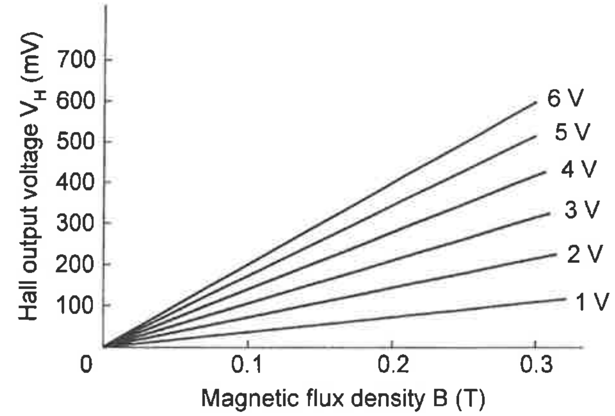

Figure 5.13 The magnetic field characteristics of Si-doped InAs Hall element (Asahi Kasei Electronics HZ-302C).

are possible. The temperature characteristics and stability of InAs Hall elements depend on the electron density in the active layer [20, 21]. The higher operation temperature (near 150°C) is attainable by optimizing Hall element design and Si doping. These Si-doped InAs Hall elements also work well at lower temperatures. It is also possible to fabricate a small package suitable for many kinds of applications.

The excellent characteristics of high stability, low offset drift, and low $1/f$ noise properties are special features of the InAs Hall elements. By using the thin-film InAs Hall element with heavy Si doping (electron density of $5 \cdot 10^{17}/cm^3$), a very small magnetic field of 0.003 mT was detected and the element showed a high sensitivity and low-noise properties. Moreover, the temperature dependence of the Hall output voltage and input resistance of heavily doped InAs Hall elements was very small, effectively near zero

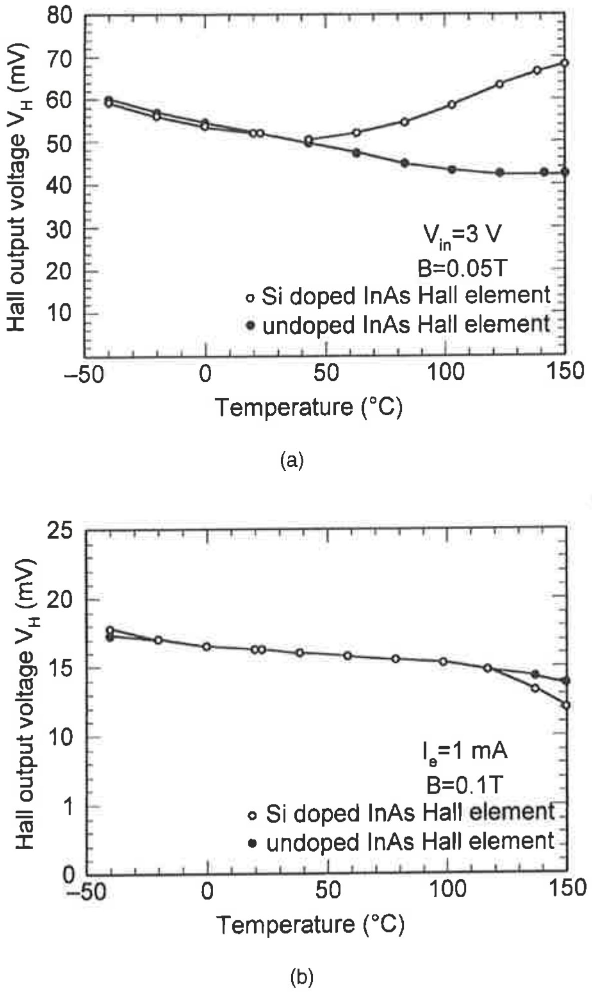

Figure 5.14 Temperature dependence of Hall output voltage for InAs Hall elements (Asahi Kasei Electronics HZ-302C): (a) constant voltage driving and (b) constant current driving.

over a wide temperature range (from −40°C to +160°C) [20]. These excellent properties of InAs Hall elements are promising for current sensor applications, magnetic field measurement, and other applications such as contactless sensors.

5.2.4 InAs Deep Quantum Wells and Application to Hall Elements

To achieve even higher sensitivity for InAs Hall elements, an even higher electron mobility and higher sheet resistance are required for the InAs active

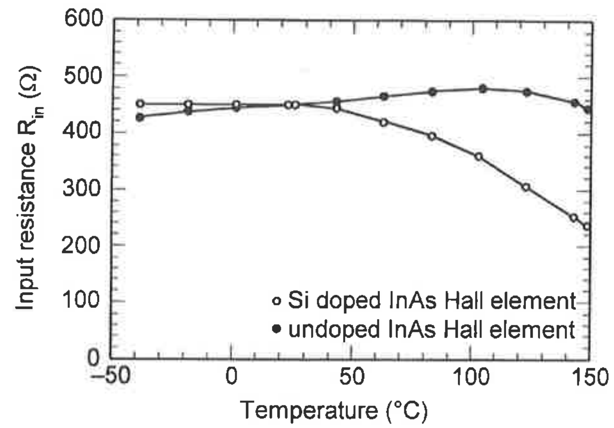

Figure 5.15 Temperature dependence of input resistance for InAs Hall elements (Asahi Kasei Electronics HZ-302C).

layer. That means an ultrathin InAs active layer with a higher electron mobility or quantum well structure is required. Next, we describe the extremely high potential of quantum well structures as magnetic sensors. To obtain a higher electron mobility, InAs deep quantum well (DQW) structures were studied. One new type of insulating layer is a quaternary material incorporating Sb having the same lattice constant as InAs and with a large bandgap energy of about 1.0 eV. This composition works well as a high potential barrier to form the InAs quantum well. For example, $Al_xGa_{1-x}As_ySb_{1-y}$ $(0 < x < 1,\ 0 < y < 1)$ is a suitable composition range. This layer absorbs many kinds of defects produced by the large lattice mismatch (7.4%) between the GaAs substrate and the InAs. Moreover, the defects are electrically inactive, and the layer acts as an insulating layer, pinning electrically active defects.

This insulating layer was used to form a DQW with a conductive InAs channel layer (i.e., InAs DQW) and applied to a Hall element [22–24]. Figure 5.16 illustrates a typical InAs DQW Hall element structure.

A 15-nm-thick InAs well was used as an active layer, and a structure comprising AlGaAsSb (35 nm)/InAs (15 nm)/AlGaAsSb(600 nm)/GaAs (at $x = 0.65$ and $y = 0.02$) was grown by MBE. The InAs DQW had a high electron mobility of 20,000–32,000 cm^2/Vs, as shown in Table 5.5.

The typical Hall output voltage from that DQW was 300 mV/0.05T/6V, as shown in Table 5.6.

The Hall output voltage was also proportional to the magnetic flux density of the applied magnetic field. The output voltage and temperature

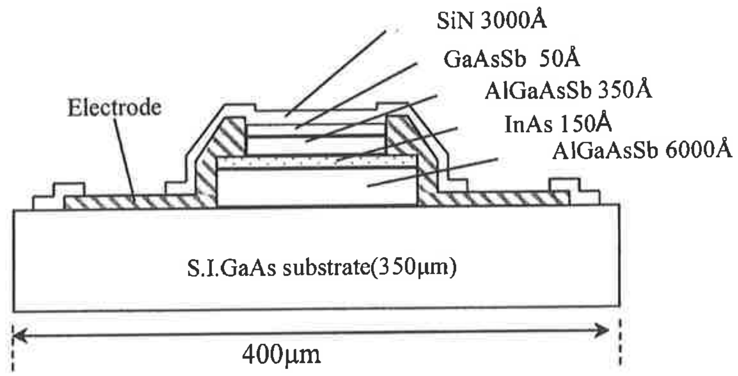

Figure 5.16 InAs DQW Hall element structure (cross section).

Table 5.5
Typical Properties of InAs DQW (at 25°C)

	Dopant	Electron Mobility, μ_H	Electron Density, n	Thickness, t
InAs DQW	None	20,000–32,000 cm^2/Vs	$50 \cdot 10^{16}$ cm^{-3}	0.015 μm

Table 5.6
Typical Characteristics of InAs DQW Hall Elements

	Driving Voltage, V_{in} (V)	Hall Output Voltage, V_H (B = 0.05T)	Offset Voltage, V_μ (B = 0T)	Resistance, R_{in}
DQW	6V	250–300 mV	<±16mV	700Ω

dependence of InAs DQW Hall elements are compared with various kinds of Hall elements in Figure 5.17.

Figure 5.17 shows that InAs DQW Hall elements have a high sensitivity comparable to InSb thin-film Hall elements with magnetically amplified structure and good stability over a wide temperature range. The InAs DQW is applicable to many kinds of sensors and electronic devices, and InAs DQW Hall elements hold promise as magnetic sensors of the future.

5.2.5 Conclusion

Hall elements formed by thin-film technology have been utilized in important applications such as magnetic sensors in electronic equipment. InSb Hall

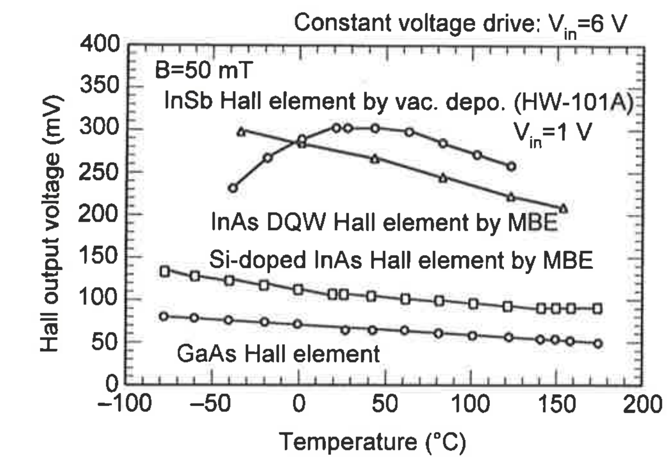

Figure 5.17 Temperature dependence of Hall output voltage for various kinds of Hall elements.

elements show ultrahigh sensitivity to magnetic fields and have resulted in revolutionizing dc brushless motor technology. The InAs Hall elements have practical characteristics of high sensitivity and temperature stability suitable for new applications. In the future, the InAs DQW Hall element will prove its usefulness with its ultrahigh sensitivity and stability over a wide range of operation temperatures. These thin-film Hall elements will open new areas of applications for magnetic sensors and will contribute to the advancement of electronic systems.

This section described only a selection of practical thin-film Hall elements that have been developed by Asahi Chemical Industry Co. Ltd. The GaAs Hall element was not described, but it also is important for practical applications. Moreover, important early applications of discrete Hall elements as contactless sensors (except from dc brushless motors) are summarized in [25, 26]. These applications may be still valuable in future.

5.3 Integrated Hall Sensors

5.3.1 Historical Perspective

The history of fully integrated Hall effect sensors closely parallels the development of linear analog bipolar integrated circuit technology. The reason for that is the natural fit of the Hall element requirements to the linear bipolar process. The Hall element can be fabricated in linear bipolar silicon with