# Simultaneous Sensing of Film Thickness and Temperature using an InSb Hall element

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## ABSTRACT

This paper describes a unique sensing method to apply an InSb Hall element that enables simultaneous sensing device to detect thickness of insulating film on an iron plate and temperature. We made a trial thickness-temperature sensor consists of an InSb Hall element and a small permanent magnet. Here, the film thickness is detected by the variation in distance between the Hall element with the magnet and the iron plate. The temperature characteristic of an InSb Hall element depends on the drive circuit to generate the Hall voltage. Therefore, the Hall element is driven using a constant voltage source and a constant current source by time-division to obtain two kinds of Hall output voltages. Two output Hall voltages driven by two kinds of bias circuits are measured in the film thickness range from 0 to 500 μm, and for a temperature range of -10 to 70 °C. The inverse response surfaces that are used to identify the thickness of insulating film and temperature are formulated using experimental results. The results obtained show that it is possible to detect film thickness and temperature by obtaining two kinds of Hall voltages.

**Keywords:** Hall element, magnetic field, thickness-temperature sensor, simultaneous sensing

## 1. INTRODUCTION

Thickness measurement of coating film is required for non-destructive soundness evaluation of iron bridges, coating film inspection, quality control, and so on. Several kinds of contact type film thickness meters are commercially available. For example, a magnetic induction method with a measurement coil and low frequency alternating magnetic field, an eddy current method based on a high frequency magnetic field, and a magnetic method with a Hall element and a permanent magnet are used as fundamental sensing methods. However, most of that have to add a temperature-compensation circuit[1] using an extra temperature sensor such as an IC temperature sensor to suppress variation in thickness incident to variation in environmental temperature for precise measurement. Therefore, a unique sensing method to apply an InSb Hall effect element, which is generally used as magnetic sensors, to simultaneous sensing device of the film thickness on a ferromagnetic material and the temperature without a temperature sensor is proposed.

Many Hall elements[2] are used as magnetic sensors in applications such as automobiles, computers, industrial control, and consumer devices because the Hall elements work to convert the magnetic field into a voltage, which is called the Hall voltage. Gallium arsenide (GaAs) and Indium antimonide (InSb) are the materials that are most commonly used in Hall elements. On the other hand, the temperature dependence of InSb Hall elements changes according to the kind of drive circuit that is employed. Here, the film thickness is detected by magnetic flux density change, and temperature is also detected using the temperature dependency of the Hall element.

In our previous work[3,4], a magnetic tactile sensor with two InSb Hall elements that enables multifunctional tactile sensing devices to detect normal contact forces and temperature was devised. We focused on the variations in the temperature dependence for different drive circuits that are used to detect the temperature without a temperature sensor. First, to demonstrate the sensing functions of both the film thickness and temperature, we performed experiments using a trial magnetic sensor with an InSb Hall element and a permanent magnet. Next, we formulated the function of an inverse response surface to identify two input parameters using two output signals (two Hall voltages). In this paper, we describe the usefulness of a Hall element as simultaneous sensing device that can be used to obtain two parameters (film thickness and temperature). This is carried out using a trial sensor with two output signals that respond to both the magnetic field and temperature.

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# 2. HALL ELEMENT

## 2.1 Hall Effect and bias mode

A Hall element is a magnetic sensor that detects a magnetic field based on the Hall effect. When a magnetic field is applied to a thin plate of semiconductor material so that it is at right angles to the current flow, as shown in Figure 1, a small Hall voltage $V_H$, appears across the plate. This is because many small charged particles such as electrons experience a force, called Lorentz force which is produced by an electromagnetic field. The Hall element can be driven by either a constant current source or a constant voltage source. Generally, a constant-current bias is used for highly sensitive measurements. In this study, InSb Hall elements were used because of the large temperature coefficient of the Hall voltage, which is driven by a constant current source for temperature sensing.

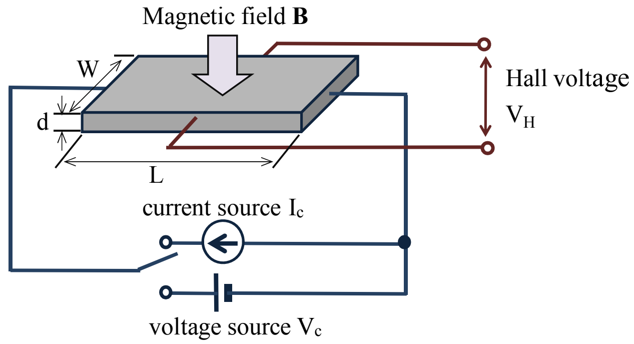


Figure 1. The Hall element and bias mode.

## 2.2 Characteristics of InSb Hall element

Figure 2 shows the Hall voltage of the InSb Hall element (HW-300B) plotted against the magnetic flux density for two kinds of drive sources at room temperature (30°C). The sensitivity at a constant voltage drive of 1 V is lower than that of the constant current drive of 5 mA. This is because the input resistance of the Hall element increases with increasing magnetic field based on the magnetoresistance. In addition, the Hall voltage of the InSb Hall element in the constant-current drive decreases with increasing temperature because of the negative temperature coefficient $\alpha_V$ (-1.8%/°C, average of between 0°C and 40°C, HW300B datasheet) of the Hall voltage shown in Fig. 3(a). The Hall voltage obtained with the constant voltage drive is independent of the temperature in the low magnetic field shown in Fig. 3(b). This is because the temperature dependence is canceled by the negative temperature coefficient $\alpha_R$ (-1.8 %/°C, average between 0°C and 40°C, HW300B datasheet) of the input resistance $R_{in}$.

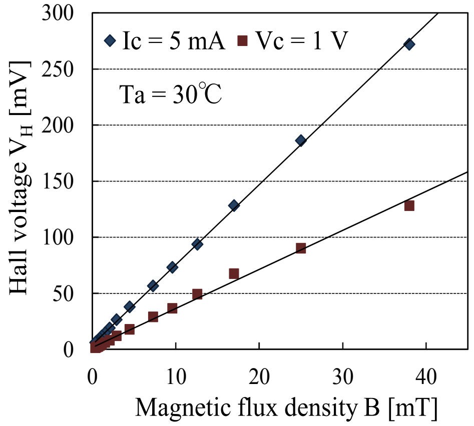
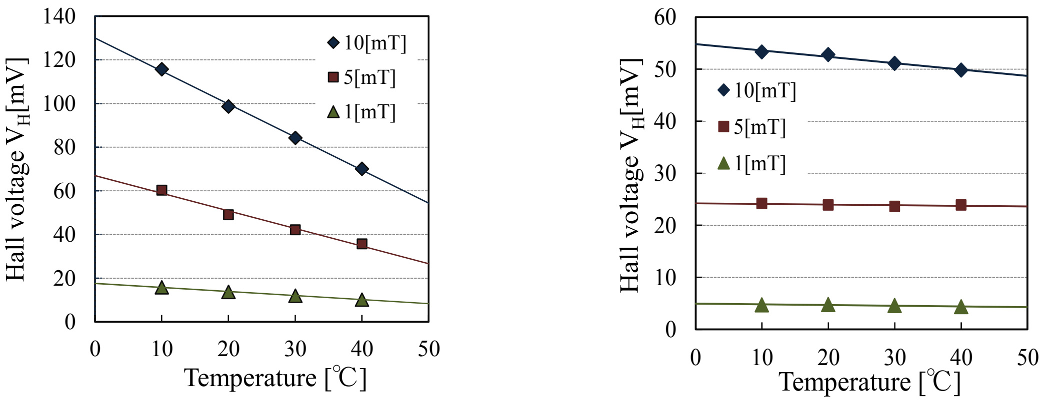


Figure 2. Hall voltage vs. magnetic flux density for InSb Hall element (ASAHI KASEI MICRODEVICES Co. HW-300B) with two kinds of drive circuits.



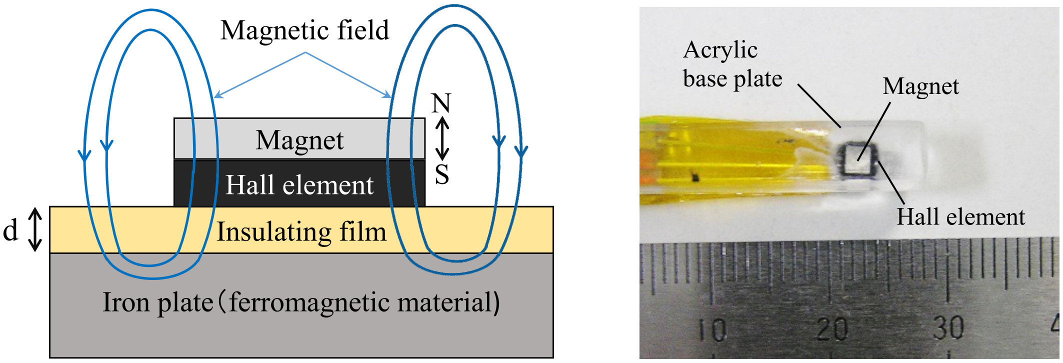
(a) (b)

Figure 3. Temperature characteristics for InSb Hall element (HW-300B). (a) Constant current bias of 5mA. (b) Constant voltage bias of 1V.

## 3. MAGNETIC THICKNESS-TEMPERATURE SENSOR

### 3.1 Structure

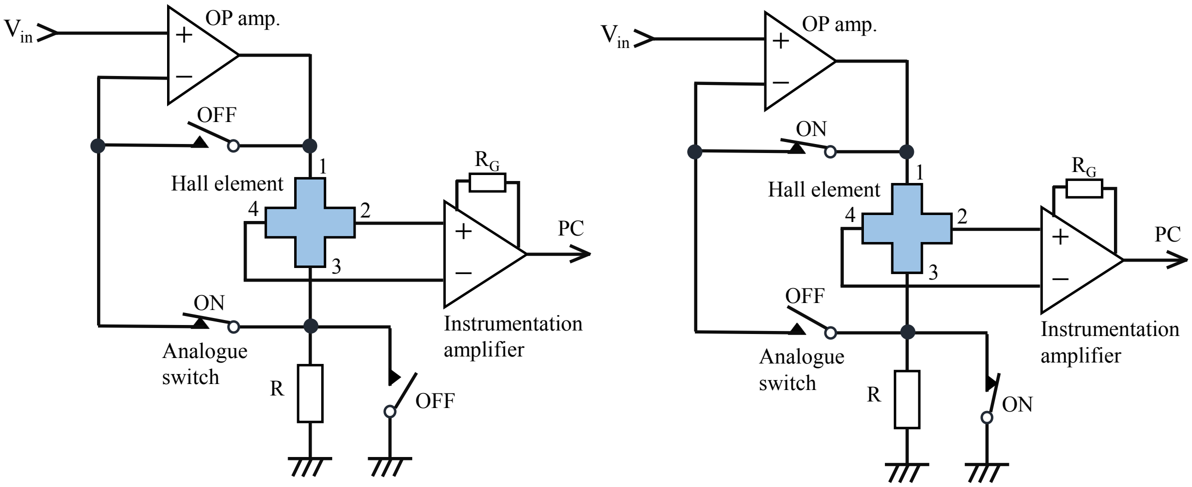
Figure 4(a) shows cross section of a magnetic thickness-temperature sensor. This sensor device consists of an InSb Hall element (HW-300B), a square plate magnet (2.0 ×2.0 × 0.5, surface magnet flux density B = 175mT), and an acrylic base plate shown in Fig.4 (b). In this study, the magnet, the Hall element, and the acrylic base plate are adhered to each other with an instantaneous adhesive. The magnetic field, which is generated by a magnet, in the Hall element is changed corresponding to the thickness *d* of the insulating film to be measured or the distance between the Hall element and the iron plate (ferromagnetic material) as shown Fig.4 (a). On the other hand, the temperature of the Hall element is changed corresponding to the temperature of the iron plate.



(a) (b)

Figure 4. Structure of the thickness-temperature sensor using an InSb Hall element and a magnet. (a) Cross section of the sensor and the object material. (b) Photograph of the back side.

The Hall element is driven with two drive modes to obtain two output signals of the sensor shown in Figure 5. The constant current mode is to enhance the temperature dependence for temperature sensing. The constant voltage mode is to neglect the temperature dependence, although there is decreased sensitivity to the magnetic field. These drive modes are switched by analogue switches which are synchronized with the switching signal. The Hall voltage is amplified by the instrumentation amplifier to transmit the Hall voltage to a PC. The amplified Hall voltages in the constant current drive and constant voltage drive are $V_1$ and $V_2$, respectively.



(a) (b)

Figure 5. Drive circuit with switching function. (a) Constant current drive mode (b) Constant voltage drive mode.

Figure 6 shows the signal flow diagram of the magnetic thickness-temperature sensor. The output voltage $V_1$ and $V_2$ of the sensor include two mixed input parameters. Finally, the input parameters are evaluated using both sensor outputs $V_1$ and $V_2$, which depend to differing extents on the magnetic field and the temperature. In the data processing step, an inverse transform function is needed to separate the input parameters from the output voltage.

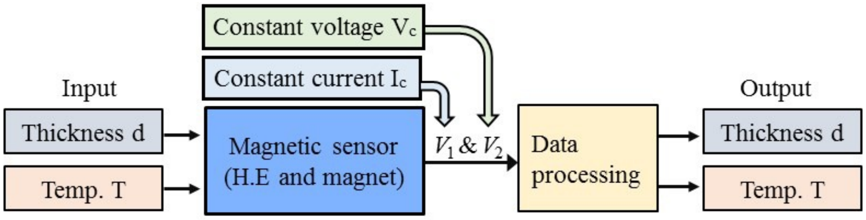


Figure 6. Signal flow diagram.

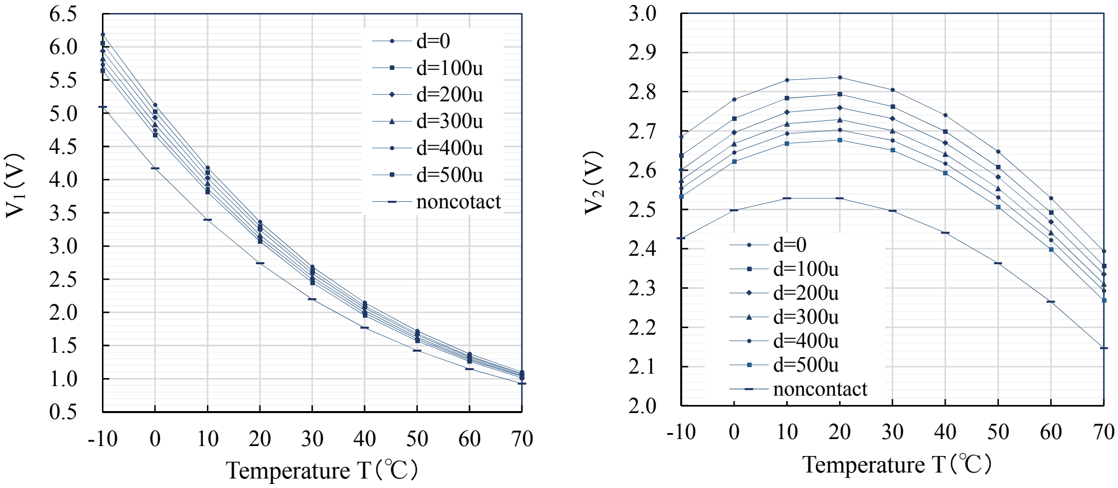
### 3.2 Fundamental characteristics

In the experiment, the output amplified Hall voltage $V_1$ and $V_2$ were measured at nine temperatures from -10 to 70 °C and six thicknesses from 0 to 500 μm using insulating film sheets using an analogue input terminal (CONTEC Co., AI1608AY-USB), and a temperature controlled chamber (ESPEC Co., SH221) to change the temperature of the sensor and an iron plate (object). The frequency of the switching signal for drive modes was 30 Hz.

Figure 7(a) and (b) show the fundamental characteristics of output Hall voltage $V_1$ and $V_2$ amplified by a factor of 4 when the thickness of the insulating film and the temperature were changed. From this result, the output $V_1$ was significantly changed by the temperature compared with output $V_2$. On the other hand, the output $V_2$ has a peak at a temperature of 20 °C although the range of output $V_2$ is narrow because of the constant voltage drive. Therefore, output voltage $V_1$ and $V_2$ can be expressed as different functions of the thickness $d$ and the temperature $T$ by the following equation.

$$V_1 = f_1(d,T) \tag{1}$$

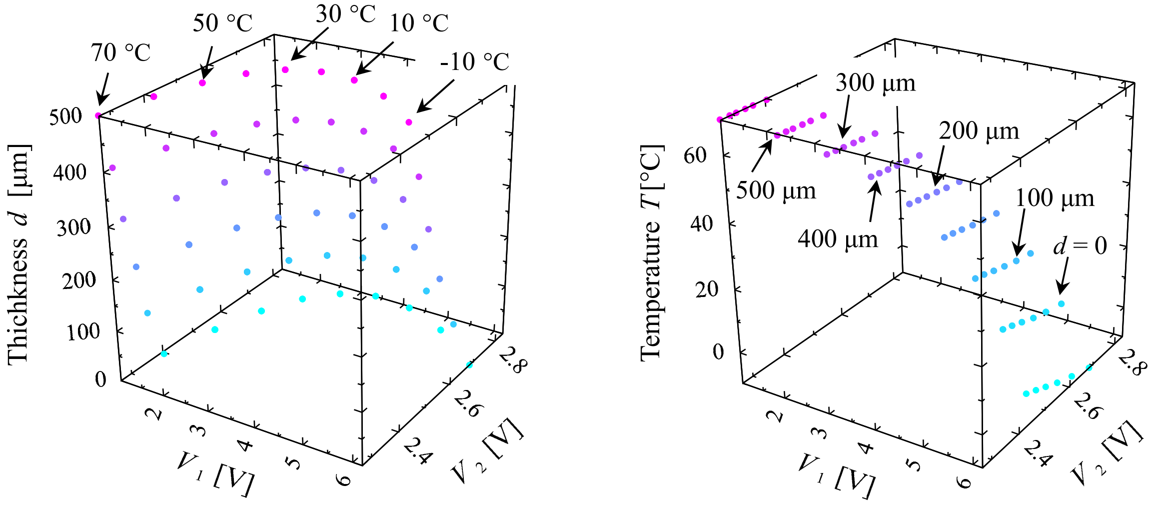
$$V_2 = f_2(d,T) \tag{2}$$



(a) (b)

Figure 7. Fundamental characteristics of the output Hall voltage. (a) Constant current drive of 0.5 mA. (b) Constant voltage drive of 2 V.

Figure 8 (a) and (b) show 3D plots that were obtained using the fundamental characteristics of the thickness $d$ and temperature $T$, respectively. We found that these 3D plots indicate gradual surface variations within this experiment range.



(a) (b)

Figure 8. 3D plot using fundamental characteristics. (a) Thickness $d$. (b) Temperature $T$.

# 4. INVERSE RESPONSE SURFACE

To obtain two input parameters of the thickness $d$ and the temperature $T$, an inverse response surface was formulated using output data of $V_1$ and $V_2$. In this study, a quadratic polynomial equation was adopted as a function of the inverse response surface because Fig.8 shows monotonous change. The quadratic polynomial equation $f\,(V_1,V_2)$ is given by the following equation:

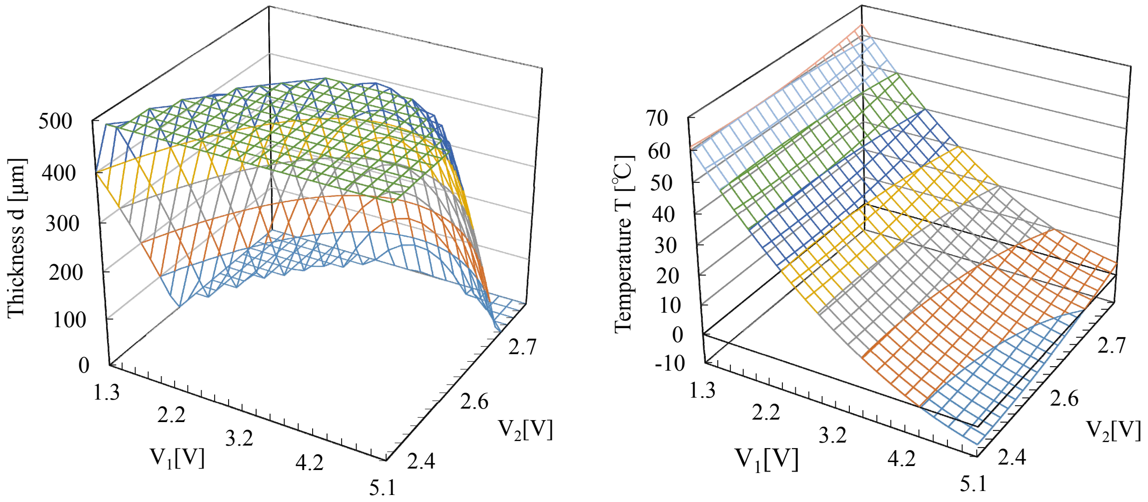
$$f(V_1,V_2)=\beta_0+\beta_1V_1+\beta_2V_2+\beta_3{V_1}^2+\beta_4{V_2}^2+\beta_5V_1V_2 \tag{3}$$

where $\beta_0$–$\beta_5$ are constant coefficients. These constant coefficients were calculated by the least square method using the fundamental characteristics. In this trial magnetic thickness-temperature sensor, the thickness $d$ and the temperature $T$, which use calculated constant coefficients of each inverse response surface, is given by the following equations:

$$d=-5.70\times10^3+9.92\times10^2V_1+6.29\times10^3V_2-1.50\times10^2V_1^2-1.76\times10^3V_2^2+35.1V_1V_2 \tag{4}$$

$$T=4.09\times10^2-47.8V_1-2.36\times10^2V_2+3.09V_1^2+45.1V_2^2+4.45V_1V_2 \tag{5}$$

Figure 9(a) and (b) show the three-dimensional inverse response surface expressed as equation (4) and (5), respectively. From these figures, the thickness $d$ or the temperature $T$ are uniquely evaluated using the output voltage $V_1$ and $V_2$. Although the response surfaces of Fig.9 are drawn in full range of the output Hall voltages, the usable ranges are within the plotted area of Fig. 8.



(a) (b)

Figure 9. Inverse response surface using the output voltage $V_1$ and $V_2$. (a) Thickness $d$. (b) Temperature $T$.

# 5. DISCUSSION

To obtain not only the film thickness but also the temperature, we investigated the temperature dependence of InSb Hall element instead of using a small temperature sensor such as a thermistor. In the case of InSb Hall element, two bias circuits with a constant current and a constant voltage were used to obtain two different sensitivities to the film thickness and the temperature. Although two drive circuits are required for this method, we can construct a thickness-temperature sensor device with very simple structure to obtain two input parameters simultaneously. The Hall element is affected by external magnetic fields. Therefore, in these environments, we require a magnetic shield to enable practical use.

## 6. CONCLUSION

We proposed a magnetic thickness-temperature sensor with an InSb Hall element, a permanent magnet for multifunctional sensing device to detect the thickness of insulating film and the temperature. The thickness was detected by the variations in the magnetic field of the Hall element corresponding to the thickness of the insulating film on the iron plate, and the temperature was detected using the temperature dependence of the Hall element. To demonstrate the sensing functions of both the thickness and the temperature, we measured two output signals of the magnetic sensor using two drive modes.

By varying the two drive circuits, which consist of a constant voltage and a constant current, the results obtained show that the two output signals have different sensitivities to the thickness and temperature. The function of the inverse response surface employed to identify two input parameters using two output signals (Hall voltages) was formulated by the least square method. It was possible to detect the thickness and the temperature by obtaining two kinds of Hall voltages. Therefore, it is useful to apply this sensing method to a new multifunctional thickness sensor composed of monomaterial Hall device.

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