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New digital magnetic sensors which consist of a compound semiconductor thin film magnetic sensor and a silicon-IC signal processing circuit in a package called hybrid Hall IC were studied. The InSb and InAs thin film Hall elements and InAs DQW Hall element were used as magnetic sensors to form the hybrid Hall ICs. These hybrid Hall ICs have a very simple structure and exhibit high sensitivity and stability. Moreover, they exhibit great potential as contactless sensors.

1. Introduction

Recently, magnetic sensors have come to be used as contactless sensors for many kinds of applications. An important type of magnetic sensor is a Hall element made of InSb thin film. A Hall element is used mainly as a magnetic sensor for small-sized brushless motors for driving VCR, FDD, CD-ROM, and so forth. The other well-known magnetic sensors are monolithic Hall effect ICs with silicon Hall elements and digital amplifiers made using silicon IC technology. They are also used in brushless motors, contactless switches, and rotation detection sensors. This type of magnetic sensor has a digital output signal corresponding to the applied magnetic field in contrast to Hall elements which have an output voltage proportional to the applied magnetic field. Both the Hall elements and Hall effect ICs are important magnetic sensors. ON-OFF detection of a magnetic field by Hall effect ICs is very simple. Therefore, recently, Hall effect ICs have been used in many new applications, including as a new contactless switch, for detection of rotating gear tooth, and as a contactless position sensor, and other types of contactless detection methods applying

Hall effect ICs are becoming important.

At present, the amount of electrical energy consumed by electric motors is about half of the total electrical power generated in Japan. The reduction of power consumption by electrical motors may be a significant issue in the future. Power brushless motors with a permanent magnet rotor and Hall effect magnetic sensors may need less electrical energy compared to conventional types of motors. The Hall motor is a motor which can change rotational speed from low to high speed by observing the position and speed of the permanent magnet rotor by using magnetic sensors. Most of the electrical systems which are driven by electrical motors need a rotary power with variable speed to reduce their power consumption. Conventional AC induction motors cannot change their rotational speed to correspond to the change of the load. Therefore, the magnetic sensor is a key and important device for future motors or actuators with low-energy consumption to realize electrical energy saving. To realize such low-energy-consumption motors, high-sensitivity and highly reliable Hall effect devices with digital output signals to detect the ON-OFF state of a magnetic field are required. A wide operation temperature range may also be required for magnetic sensors for these applications because such motors are always used in extreme environments.

Silicon is sensitive to mechanical stress and silicon Hall elements have very low sensitivity in a magnetic field. These properties posed many difficult problems for silicon monolithic Hall effect ICs (or Hall ICs) such as low sensitivity, large offset voltage to signal voltage ratio and the effect of external stress. Thus, the silicon monolithic Hall effect IC is not satisfactory for those applications.

Hall ICs having a hybrid structure with digital output signal and combining a high-sensitivity Hall element made from a compound semiconductor thin film as a magnetic sensor and a silicon-IC signal processing circuit in a package (i.e., Hybrid Hall effect IC or hybrid Hall IC) show great promise as noncontact magnetic sensors that are highly sensitive, highly reliable and highly stress resistant and have a wide operation temperature range.

The electron mobility of thin-film InSb and InAs grown on GaAs substrates is 10 to 30 times larger than that of Si. Therefore, we can fabricate high-sensitivity Hall elements with a very small ratio of offset voltage to signal voltage. Also, these Hall elements are not so sensitive to external stress and noise. Therefore, high-sensitivity in magnetic fields and stability under external stress will render InSb and InAs Hall elements suitable as magnetic sensors for hybrid Hall ICs.

In this paper, we have fabricated and studied a hybrid Hall IC having a compound semiconductor thin film Hall element as a magnetic sensor.

2. InSb Thin Film Hybrid Hall IC

An InSb Hall element with magnetic field amplification structure has high sensitivity in a magnetic field. This magnetic field amplification structure means a Hall element having a sandwiched structure where a magnetically sensing portion of InSb thin film is sandwiched by ferrite substrate and a chip for collimating magnetic field. Thus, the Hall element has high sensitivity. The typical characteristics are shown in Table1.[1–3]

This InSb thin film Hall element chip was combined with a silicon-IC signal processing

circuit amplifier chip (silicon IC amplifier chip) in a package to form a digital output magnetic sensor. The silicon IC amplifier chip was fabricated by conventional bipolar IC processes. The fabrication process of hybrid Hall ICs is easy and simple where the Hall element chip and IC chip are connected by gold wires on a lead frame island and packaged by an epoxy resin molding process which is a simple well known process used for the assembly of electrical devices.

A simple block diagram of the concept of the hybrid Hall IC is shown in Fig. 1 and the two basic types of operation modes are shown in Figs. 2(a) and (b). In Fig. 2 (a), by applying a magnetic field exceeding Bop, the output voltage Vout of high level V_{off} (=Vcc) reduces to a low level of V_{on} and by reducing the applied magnetic field below Brp, the output voltage Vout of low-level V_{on} changes to a high level of V_{off}. Bop–Brp =Bh > 0 is the hysteresis value of the operational magnetic field. In Fig. 2 (b), similar operation mode by alternating the magnetic field is shown.

A special direct-coupled amplification method is used here as a signal processing amplifier that directly converts the Hall output voltage of the InSb Hall element to the desired digital signal. We also optimized the resistance and the temperature coefficients of resistors used in the signal processing circuit corresponding to a large temperature depen-

Table 1
Typical magnetic field characteristics of the Hall element chips.

Magnetic sensor	InSb thin film Hall element
Hall voltage	200 mV/1 V, 50 mT
Input resistance	350 Ω
Output resistance	350 Ω
Offset voltage	<±7.0 mV/1 V

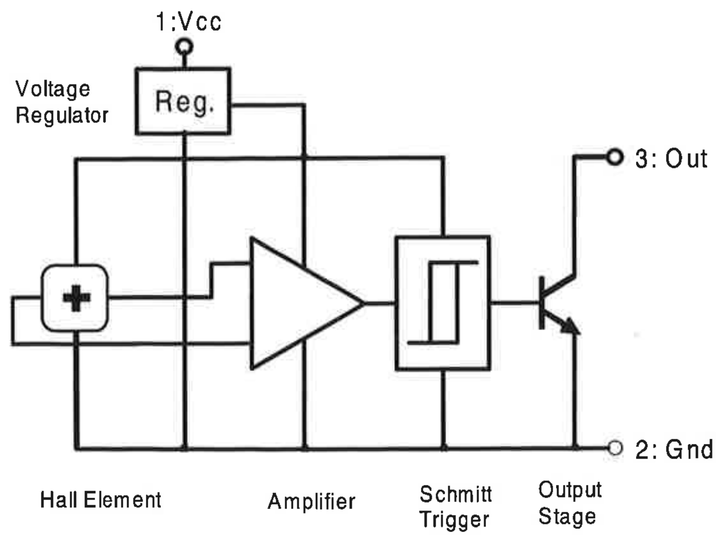

Fig. 1. Schematic diagram of hybrid Hall IC.

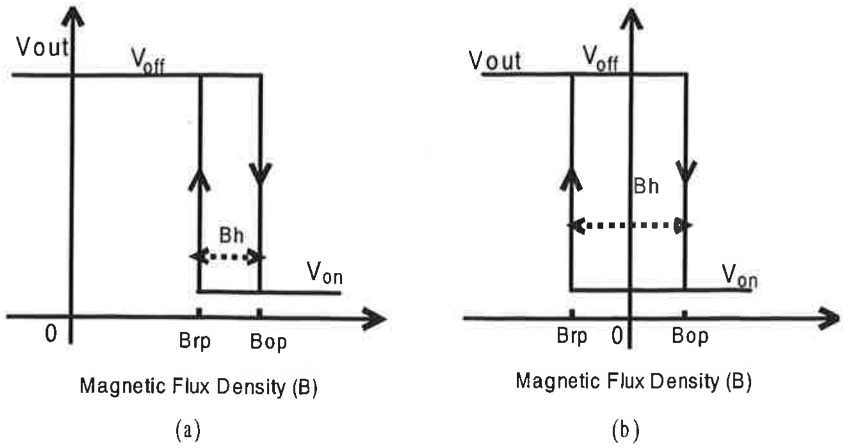

Fig. 2. Operational characteristics with hysteresis loop of hybrid Hall IC.

Table 2
Typical characteristics of hybrid thin film Hall ICs.

Magnetic sensors	InSb thin film Hall element	InSb thin film Hall element
Vcc	4.5 to 24 V	4.5 to 24 V
Bop	12.0 mT	3.2 mT
Brp	9.0 mT	2.4 mT
Vout(B>Bop)	V_{on}< 0.2 V	V_{on}< 0.2 V
Vout(B<Brp)	V_{off}=Vcc	V_{off}=Vcc
Operating temp.	–20 to +115°C	–20 to +115°C

Vcc is operating voltage of hybrid Hall ICs.

dence of the InSb Hall element for temperature stability. The typical characteristics of the hybrid Hall effect ICs with InSb Hall elements are shown in Table 2. A photograph of the hybrid Hall effect ICs with InSb Hall element and Si IC amplifier chip (no package) is shown in Fig. 3(a). The plastic packaged hybrid Hall ICs are shown in Fig. 3(b).

The standard Si monolithic Hall ICs have a Bop of about 20 mT. We fabricated two types of thin film hybrid Hall ICs. One of them has Bop under 15 mT around room temperature and the other has under 4 mT as shown in Table 2. These Bop values indicate the high sensitivity of hybrid Hall ICs due to the use of InSb thin film Hall elements.

The operation temperature range for these hybrid Hall effect ICs is –20 to 115°C. The typical temperature dependence of the operation magnetic field of the hybrid Hall effect IC is shown in Fig. 4. The stress effect of the hybrid InSb thin film Hall ICs is very small or negligible.

The operating magnetic field Bop (typical value: 20 mT) of a commercial Si monolithic Hall IC showed a random variation of ±4 mT by compressive stress application from 0 to 2.5 MPa. These characteristics reveal that the hybrid InSb thin film Hall IC may be of high sensitivity, reliable and practical for many kinds of applications.

(a)

(b)

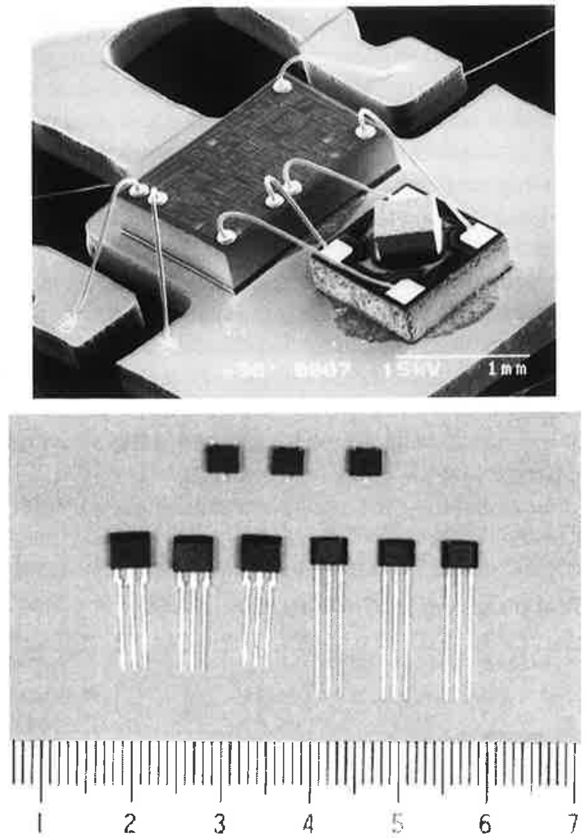

Fig. 3. Photographs of InSb thin film hybrid Hall ICs. (a) The hybrid Hall effect ICs with an InSb Hall element having magnetic field amplification structure and a Si IC amplifier chip (no package) (b) Plastic packaged hybrid Hall ICs.

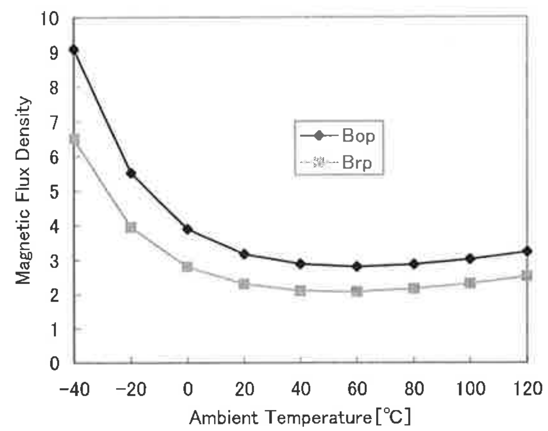

Fig. 4. Temperature dependence of the operation magnetic field of hybrid InSb thin film Hall IC.

3. InAs thin film and InAs DQW hybrid Hall IC

The InSb thin film hybrid Hall IC is practical and has high sensitivity, however, the operating temperature is restricted to approximately room temperature.[1,3] Some recent applications of digital magnetic sensors require more severe operating conditions. To realize a wide operating temperature range of hybrid Hall ICs, Hall elements with a small temperature dependence must be used as magnetic sensors.

Si-doped 0.5 μm InAs thin film Hall elements (Si-doped InAs H.E.) and InAs deep quantum well Hall elements (InAsDQW H.E.) grown on GaAs substrates by MBE show high sensitivity and stable operating characteristics over a wide temperature range.[3-6] These Hall elements were used to fabricate hybrid Hall effect ICs and their characteristics were studied. The standard characteristics of these Hall elements are tabulated in Table 3.

A Si-doped InAs hybrid Hall IC has a structure which consists of a Si-doped 0.5 μm InAs thin-film Hall element and a silicon IC fabricated by conventional processes. We optimized the resistance and the temperature coefficients of resistors used in the signal processing circuit corresponding to temperature characteristics of the InAs Hall element

Table 3
Typical magnetic field characteristics of the Hall element chips.

Hall elements	Si doped InAs Hall element	InAs DQW Hall element
Hall voltage	100 mV/6 V, 50 mT	200 mV/6 V, 50 mT
Input resistance	300 Ω	350 Ω
Output resistance	300 Ω	350 Ω
Offset voltage	—	—

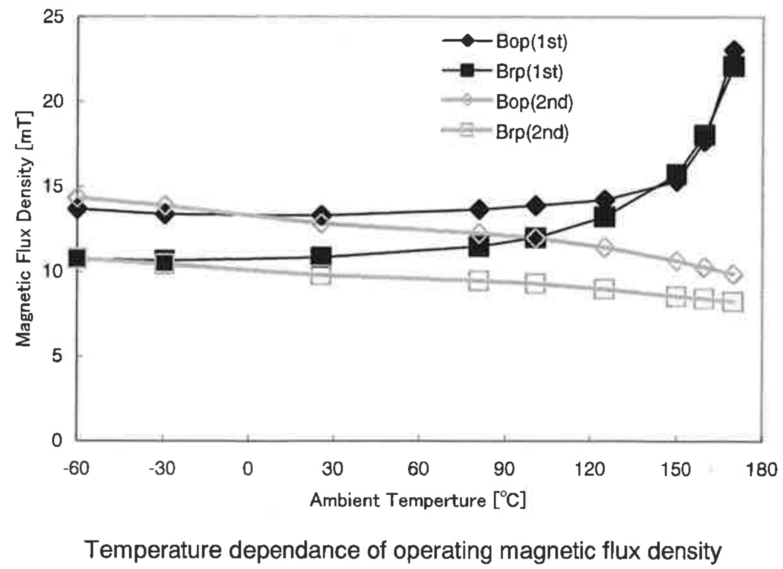

Fig. 5. Temperature dependence of hybrid InAs thin film Hall IC (dotted lines denote the improved switching characteristics: 2nd fabrication).

for temperature stability over a wide temperature range.

The simple combination of an InAs Hall element and a Si IC amplifier of a Si-doped InAs hybrid Hall IC was problematic at higher temperatures. A large increase of leakage current to the substrate in a Si IC chip may have the effect of reducing hysteresis B_H at higher temperatures. This is shown in Fig. 5, which shows the large effect of the leakage current and hysteresis B_H gradually decreasing to zero and normal switching operation above 130°C is almost impossible.

To improve the switching characteristics at high temperatures, we have adopted a transistor with very low collector resistance whose structure can be fabricated within conventional IC processes and whose switching function does not degrade due to leakage current at high temperatures. As a result, the operation characteristics of a Si-doped InAs hybrid Hall IC show stable temperature characteristics from –60°C to high temperature of 170°C (2nd fabrication). This is shown in Fig. 5. Typical characteristics of the hybrid InAs thin film Hall IC are shown in the first column of Table 4.

Using the same Si IC amplifier, the InAs DQW Hall element is also combined to fabricate an InAs DQW hybrid Hall effect IC. In this case, high sensitivity and stable temperature characteristics are also verified from a low to high temperature. The results are shown in the second column of Table 4. The operation characteristics for various hybrid thin film Hall ICs are shown in Fig. 6.

Table 4
Typical characteristics of hybrid Hall ICs.

Magnetic sensors	Si doped InAs Hall element	InAsDQW Hall element
Vcc	4.5 to 28 V	4.5 to 28 V
Bop	12.0 mT	5.5 mT
Brp	9.0 mT	4.0 mT
Vout(B>Bop)	V_{on}< 0.1 V	V_{on}< 0.1 V
Vout(B<Brp)	V_{off}=Vcc	V_{off}=Vcc
Operating Temp.	–50 to +170°C	–50 to +170°C

Vcc is operating voltage of hybrid Hall ICs.

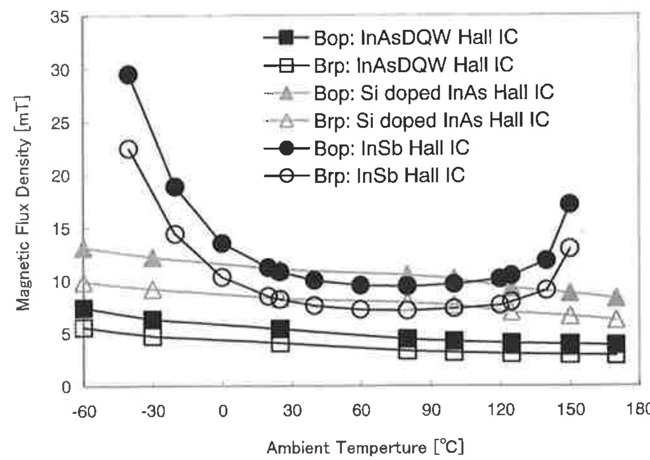

Fig. 6. Temperature dependence of the operation magnetic field of various types of hybrid Hall ICs.

4. Conclusions

Hybrid Hall ICs or Hall effect ICs having a compound semiconductor Hall element as a magnetic sensor and Si monolithic amplifier chip for signal processing to produce digital output corresponding to a detected magnetic field were developed and showed high sensitivity, stability and ease of fabrication by means of simple conventional package fabrication technology. The simple fabrication process of hybrid Hall ICs is inexpensive. These new hybrid Hall ICs will open up many new applications such as contactless sensors for power brushless motors to decrease energy consumption, contactless rotation sensors for automobile engines, contactless switches and other applications.

These hybrid Hall ICs may be key devices in future for the fine control of many kinds of actuators required by electronic systems.

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Kazutoshi Ishibashi was born in Arita, Japan, in 1961. He received the B.S. degree in engineering from Kyushu Institute of Technology, Japan, in 1984. He joined the Asahi Kasei Electronics Co., Ltd., Japan, in 1984. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

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He was born in Saitama, Japan, in 1942. He received a B.Sc. in physics from Tokyo University of Science in 1996, and an M.Sc. in 1998 and a Ph.D. in 1971, both in theoretical physics, from the former Tokyo University of Education (now the University of Tsukuba) in Japan. After pursuing research work in the Department of Physics at Tokyo University of Education, he joined to Asahi Chemical Industry Co., Ltd. in 1974 and initiated research on magnetic sensors. He developed high-sensitivity InSb thin film Hall sensors. He received a Commendation award in 1996 as "a person of scientific and technological merits" for the development of high-sensitivity thin-film Hall elements, from The Japanese Ministry of State for Science and Technology.

Dr. Shibasaki is currently working on narrow band-gap semiconductor thin films and their application as practical magnetic sensors. He is a member of the IEEE, the Institute of Electrical Engineers of Japan, the Japan Society of Applied Physics, the Physical Society of Japan, and the Magnetics Society of Japan.