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Mass production of InAs Hall elements by MBE

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Abstract

Hall elements as mass production magnetic sensors are a new application area for thin film technology such as vacuum deposition and MBE. Highly sensitive InSb thin film Hall elements formed by vacuum deposition are often applied as magnetic field sensors for small DC brushless motors used in electronic equipment. InAs Hall elements developed and produced by MBE have high sensitivity and stability over a wide temperature range and have potential for the present and future applications required by many electronic systems. Here, we review the recent status of applications, production, and the good characteristics of InAs Hall elements for use as magnetic sensors. Our production MBE system has confirmed the feasibility of high yield, mass production of thin film InAs Hall elements.

Keywords: InSb Hall element; InAs Hall element; Mass production MBE; InAs quantum well

1. Introduction

Recently, there has been a strong demand for Hall elements in the field of electronic equipment such as video cassette recorders (VCRs), personal computers with floppy disk drives (FDDs), compact disk read-only memory (CD-ROM) drives, and other electronic systems where Hall elements are mainly used as magnetic sensors in the brushless motors of these devices.

For these applications, we developed highly sensitive InSb thin film Hall elements fabricated by vacuum deposition [1]. About 800 million of these InSb Hall elements were produced and sold commercially in 1995, which covers approximately 70% of the world market. Moreover, many new future applications of contactless sensors that are Hall elements for magnetic field sensing are expected because these sensors can detect static magnetic fields as well as variable magnetic fields.

These new applications require high reliability and an operation range extending from low temperatures far below 0°C to high temperatures far above 100°C. For example, Hall elements used for automotive sensors in the engine compartment require stable operation at 150°C, and recent applications for current sensors require stable sensing of very weak magnetic fields. The Hall elements must have high sensitivity and low noise properties.

The only problem with InSb Hall elements is that their narrow operation temperature range, which is restricted to near room temperature, is not sufficient for some of these new applications. Commercially available GaAs Hall elements fabricated by ion-implantation are stable at higher temperatures. However, they, too, cannot be used for some

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of those new applications because of lower sensitivity to magnetic fields and an offset drift that arises at low temperatures below 0°C.

The MBE grown 0.5 μm thick InAs that is lightly doped with Si, without any intermediate layer on GaAs (100) substrate, shows stable temperature properties and a high electron mobility of ~ 10 000 $cm^2/V \cdot s$. We used this InAs thin film to develop a new InAs Hall element that has a wider range of operation temperature than InSb Hall elements as well as about 50% higher sensitivity than the GaAs Hall elements [2, 3]. Moreover, this Hall element has high stability for pulse voltage noise, low offset drift, and low $1/f$ noise properties, all of which are excellent properties for sensing weak magnetic fields.

For mass production of this InAs Hall element, we designed a production MBE system with a multi-wafer substrate holder that has a large growth area (a substrate holder with twelve 2-in. wafers).

Under standard production growth conditions, a high yield of more than 98% was obtained for production of InAs thin films by MBE and also high device yield for InAs Hall elements. Furthermore, since the start of production, 5 million of these MBE Hall elements have already been applied as magnetic sensors in practical devices (DC current sensors, brushless motors, etc.).

However, InAs thin films grown directly on GaAs have not shown the high electron mobility observed in bulk InAs single crystals. To obtain a higher electron mobility, the use of an InAs deep quantum well (DQW) structure is investigated. DQWs were grown by using undoped insulating layers lattice matched to InAs (i.e. AlGaAsSb(35 nm)/InAs(15 nm)/AlGaAsSb(600 nm)/GaAs). This DQW has a high room temperature electron mobility of 20 000–32 000 $cm^2/V \cdot s$. The typical Hall output voltage of this DQW Hall element is 300 mV/(0.05 T · 6 V) (high sensitivity) and the temperature dependence of the Hall output voltage is very small over a wide temperature range. InAs DQW Hall elements hold promise as future magnetic sensors, and we confirmed that DQW can also be produced in a large growth area MBE system or multi-wafer MBE system, which opens up a new DQW production technology.

2. Highly sensitive InSb Hall elements and their problems

In the early stages, InSb Hall elements were fabricated mainly from thin single crystal InSb. That type of Hall element was an expensive device and not suitable for mass production. There existed a strong need for low price, low cost and mass production Hall elements with high sensitivity to magnetic fields for use in consumer electronic systems.

For this purpose, we developed highly sensitive InSb thin film Hall elements with a novel high sensitivity structure and a mass production process for them. This Hall element opened up a new area for brushless DC motor technology and later resulted in large scale application of Hall elements as magnetic sensors in small DC brushless motors [1, 4].

Novel production technology for InSb polycrystal thin films with high electron mobility of more than 20 000–30 000 $cm^2/V \cdot s$ and 0.8 μm thick on thin mica substrates (1st row of Table 1) was established by multi-source vacuum deposition with time dependent (variable) substrate heating similar to MBE.

For the InSb thin films formed by vacuum deposition, we found some new important properties. The temperature dependencies of the Hall coefficients and conductivity were similar to those of single crystal InSb. However, the electron mobility had a very small temperature dependence near room temperature, differently from the single crystal InSb. This is because InSb thin film formed on thin mica substrate by vacuum deposition is polycrystalline. This is a very important property which has led to the discovery of a new driving method

Table 1
Properties of InSb and InAs thin films and InAs DQW

	Dopant	Electron mobility μ_H ($cm^2/V \cdot s$)	Electron density n ($\times 10^{16}$ cm^{-3})	Thickness d (μm)
InSb	None	20 000–30 000	2	0.8
InAs	Si	11 000	8	0.5
DQW	None	20 000–32 000	50	0.015

with small temperature dependence of Hall output voltage for the practical thin film InSb Hall elements fabricated by vacuum deposition.

A high sensitivity device structure of the InSb thin film Hall element was established. InSb thin film removed from thin mica substrate used for the magnetically sensitive portion of the Hall element was sandwiched between a ferrite substrate and a small ferrite chip. This structure amplifies the magnetic field in the gap between the ferrite substrate and chip by a factor of about 3–6 compared to the original magnetic field applied to Hall element. Therefore, since the InSb thin film in the gap experiences the amplified magnetic field, the Hall elements have ultra-high sensitivity to the magnetic field. This special structure is shown in Fig. 1. The first row of Table 2 shows typical characteristics of InSb high sensitive Hall elements for commercial products.

A new driving method was developed for the high sensitivity Hall elements. Since our Hall element has high input resistance of around 350 Ω, the thin film InSb Hall element is stable under a limited input voltage and is driven at constant voltage, which has never been realized for conventional crystalline single InSb Hall elements. This constant voltage driving results in the Hall output voltage of our highly sensitive InSb Hall elements having a very small or stable temperature dependence near room temperature, the same as for electron mobility. This new driving technique reduces the temperature coefficient of the Hall output voltage from -2.0%/deg to ± 0.1–0.2%/deg near room temperature. This is one of the most important practical merits of our highly sensitive InSb thin film Hall elements, and it is now a standard driving method. These Hall elements have ultra-high sensitivity to magnetic fields, practical reliability, and allow many kinds of small package designs that are good for applications.

The first practical application of our highly sensitive Hall element was the magnetic sensor for music record player motors. This first application confirmed our Hall element as a practical magnetic sensor for brushless motors. Since that application, our Hall elements have been mass produced and have served in many applications. Recent major applications include DC brushless motors or Hall

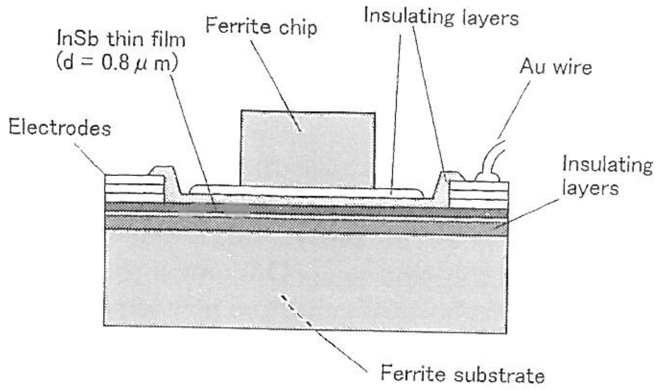

Fig. 1. The highly sensitive InSb Hall element (cross-section).

Table 2
Characteristics of InSb, InAs, and InAs DQW Hall elements

	Driving voltage V_{in} (V)	Hall output voltage V_H (mV) ($B = 0.05$ T)	Offset voltage V_u (mV) ($B = 0$ T)	Resistance R_{in} (Ω)
InSb	1	150–320	$< \pm 7$	240–550
InAs	6	100	$< \pm 16$	400
DQW	6	250–300	$< \pm 16$	700

motors used in VCRs, FDD motors, CD-ROM drive motors of personal computers, and similar electrical equipment. In 1995, more than 800 million of these InSb thin film Hall elements were produced by vacuum deposition and used in many kinds of applications (mainly magnetic sensors for DC Brussels motors).

Some problems relating to these Hall elements should be discussed. The success of these Hall elements as magnetic sensors lead to many new applications for Hall elements incorporating the functions of contactless sensing and static magnetic field sensing. These new applications impose more severe operation conditions on the Hall elements. A typical new application is automotive sensors in the engine compartment or outside the body frame. These applications require a wide operation temperature range of from -40°C to 150°C.

The only problem with the InSb Hall elements is a narrow operation temperature range, such as from −10°C to 100°C. This is because of the large temperature coefficient for input resistance of −2.0%/deg. This operation range is not sufficient for some of the new applications. However, there is strong demand for Hall elements with high sensitivity and wide operation range for recent applications such as current sensors, automotive sensors, industrial sensors, and so on. Our aim in research on new Hall elements is to suit those new applications.

3. MBE growth of InAs thin films for Hall elements and their production MBE system

Single-crystal InAs has a high electron mobility of more than 30 000 $cm^2/V \cdot s$. The InAs thin films grown by MBE also has a high electron mobility and has a wider band gap energy than InSb. Thus, it is one promising material for use in Hall elements that are both highly sensitive and stable over a wide temperature range as practical magnetic sensors [3–5]. To reduce the temperature dependence of Hall output voltage for InAs Hall elements at higher temperatures, n-type impurity doping of InAs was effective (This is also valid for a InSb Hall element) [6]. Thus, InAs was Si doped during MBE growth.

A 0.5 μm thick InAs thin film doped with a suitable amount of Si and grown directly on GaAs(1 0 0) substrate shows a high electron mobility of ~10 000 $cm^2/V \cdot s$. The electron mobility and resistivity of this thin film show very little temperature dependence over a wide temperature range. Using this InAs thin film, we developed InAs Hall elements having about 50% higher sensitivity than GaAs Hall elements and a wider operation temperature range than InSb Hall elements. The Hall output voltage of this element has good linearity in magnetic field as well as other very good properties as magnetic sensors [2, 3].

3.1. Preparation of production MBE system

For mass production of InAs Hall elements, we designed a production MBE system with three chambers and a large growth area or multi-wafer holder having throughput of more than 100 million Hall elements per year. The most important issue in designing production MBE systems is the engineering of a mass production system. Many problems special to production systems have arisen. For example, easy maintenance is very important in a production system.

Some features of our production MBE system with three chambers are listed below.

(1) A large vertical growth chamber with 1 100 mm diameter;

(2) A wafer holder with twelve 2-in. substrates (large growth area);

(3) Thickness uniformity design and substrate rotation system;

(4) 10 source ports with large diameter flanges;

(5) Specially designed Knudsen cells with large capacity (from 100 to 300 cc or more);

(6) Stable substrate heating system in growth chamber;

(7) Entry chamber with 11-wafer holder;

(8) Wafer holder transfer system employing magnetic coupling;

(9) Simple operation;

(10) Easy, automated operation;

(11) High throughput.

The purpose of the large diameter chamber is to reduce warm up of the inner surface of the chamber caused by strong radiation from the substrate heater during operation. Other important points considered in designing the system are reducing power consumption in the vacuum chamber for reducing undesired out gassing from the chamber wall and inner housing during operation, to reduce thermal interaction between source and substrate by radiation from sources, and stable substrate and source heater control. Reducing liquid nitrogen consumption is also very important for low product cost.

3.2. Growth conditions and throughput for production MBE system

We found standard growth conditions for InAs thin film with Si-doping on GaAs substrates [5]. Growth time of within 1 h was established. Simple estimation of the production capacity of our MBE system is more than 100 million Hall effect devices per year. This value is sufficient for mass production of Hall elements.

4. Production MBE growth of InAs thin films and fabrication of InAs Hall elements

4.1. MBE growth

We have grown Si doped InAs thin films (0.5 μm on GaAs (1 0 0) substrate (2° off) without an intermediate buffer layer by MBE [2, 7]. There is a well-known large lattice mismatch between InAs and GaAs about (7.2%). However, we found optimized growth conditions for InAs thin films with no such trouble for Hall element application. This InAs thin film has a two layered structure with respect to electron mobility in the growth direction. The layer farthest from the substrate interface has a higher electron mobility and is doped with Si donor atoms to obtain a high electron mobility [3, 5].

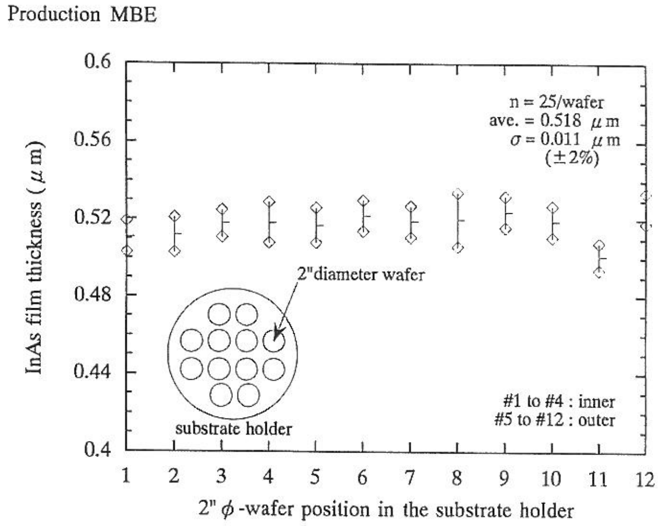

Fig. 2. Uniformity of InAs thin film fabricated by production MBE (film thickness).

4.2. Uniformity in electrical properties of InAs thin film fabricated by production MBE

Fig. 2 shows the thickness uniformity of Si doped InAs thin films grown on semi-insulating GaAs substrates by the production MBE system. Fig. 3 shows the uniformity of the electron mobility and sheet resistance. The values are sufficient for high yield of Hall effect device. Twelve InAs thin films grown on GaAs substrates by production MBE are shown in Fig. 4. We have obtained 95% yield with the MBE operation within suitable specifications restricted according to device characteristics. We experienced good reproducibility with the production MBE system. Moreover, whatever problems we experienced for thin films grown by MBE, the MBE system always had corresponding problems. This is the most beautiful and reliable point ever experienced in vacuum deposition. This means MBE is suitable as a production system.

4.3. Fabrication of InAs Hall elements

We have designed practical Hall elements which use 0.5 μm thick InAs thin films grown directly on (1 0 0) GaAs substrate. The standard electron density and mobility of InAs thin film are $8 \times 10^{16}/cm^3$ and $11\,000\ cm^2/V \cdot s$, respectively (2nd row of Table 1). InAs thin films are processed to form Hall elements by a specially developed wafer process and assembled in a commercial mass production line. This Hall element has a $0.36\ mm^2$ chip size. The fabrication process is shown in Fig. 5. An average yield of more than 96% for Hall element chips on wafer has been achieved for the wafer process. The InAs Hall element chip bonded on a lead island is shown in Fig. 6. The final product is also shown in Fig. 7.

4.4. Typical characteristics of mass production InAs Hall elements

The typical Hall output voltage (or sensitivity) of this Hall element in magnetic field is 100 mV/(6 V × 0.05 T). This is tabulated in the second row of Table 2 and is compared to the values for other Hall elements. The temperature dependence of Hall output voltage for a wide temperature range and sensitivity is shown and compared with various other kinds of Hall elements in Fig. 8.

This InAs Hall element has no problem at lower temperature where InSb Hall elements and GaAs Hall elements sometimes have suffered problems resulting from their material properties. Since the input resistance of this InAs Hall element does not change much with temperature, practical application in a wide temperature range is possible. The range depends on the electron density in the active

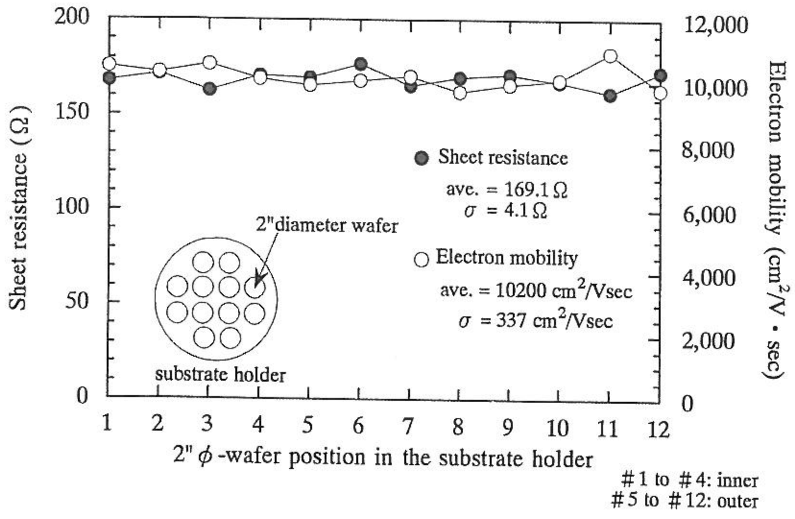

Fig. 3. Uniformity of InAs thin film fabricated by production MBE (sheet resistance and electron mobility).

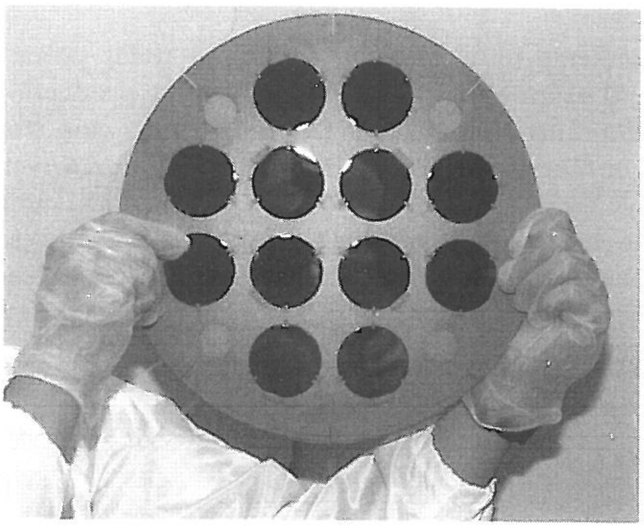

Fig. 4. Photograph of 12 InAs thin films grown on GaAs 2 in. wafers by production MBE.

layer [5]. The Hall element chip size and sometimes the package, etc., are also important factors affecting the operation temperature range. The higher operation temperature (near 150°C) required by automotive sensors in engine the compartment would be attainable by optimizing element design. These are important factors in determining the maximum rating of practical Hall elements. A small package suitable for small DC motors is possible.

Strong stability against pulse voltage noise and very low offset voltage drift are observed. Very low $1/f$ noise is also a feature of this Hall element. Low noise detection of very weak magnetic fields required by current sensor applications may be possible. Minimum magnetic field sensitivity of 0.003 mT was measured for MBE InAs Hall elements with a heavy Si doping (electron density of $5 \times 10^{17}/cm^3$) and 0.05 mT was measured for GaAs Hall elements. This small minimum detection level is very important for current sensor applications. Moreover, the Hall output voltage and input resistance of this heavily doped InAs Hall element have very small, nearly zero, temperature dependence over a very wide temperature range (from − 40 to 160°C). These fine properties are all good for current sensor applications, magnetic field measurement and other applications as a contactless sensor [4, 5]. These new features of InAs Hall elements will be suitable for new future applications.

5. InAs deep quantum wells and application to Hall elements

To realize even higher sensitivity for InAs Hall elements, a even higher electron mobility and higher sheet resistance is required for the InAs active layer. This means that an ultra-thin InAs active layer with a higher electron mobility is required. A InAs thin film 0.5 μm thick, grown directly on GaAs has lower electron mobility than bulk InAs

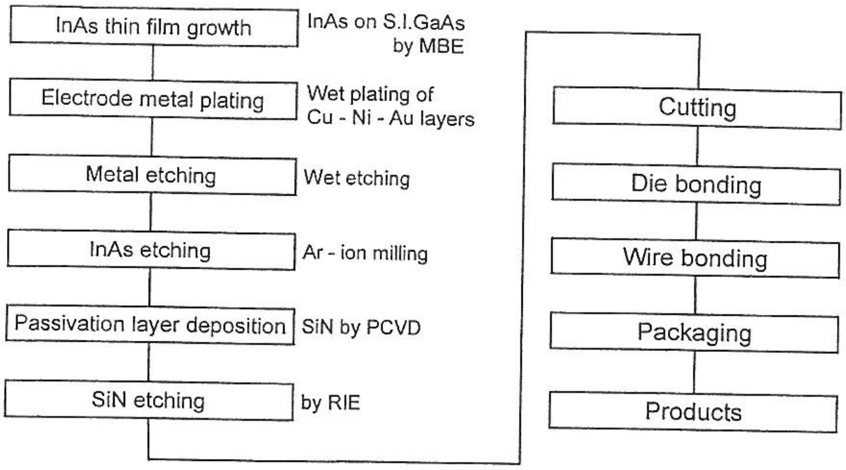

Fig. 5. Fabrication process of InAs Hall elements.

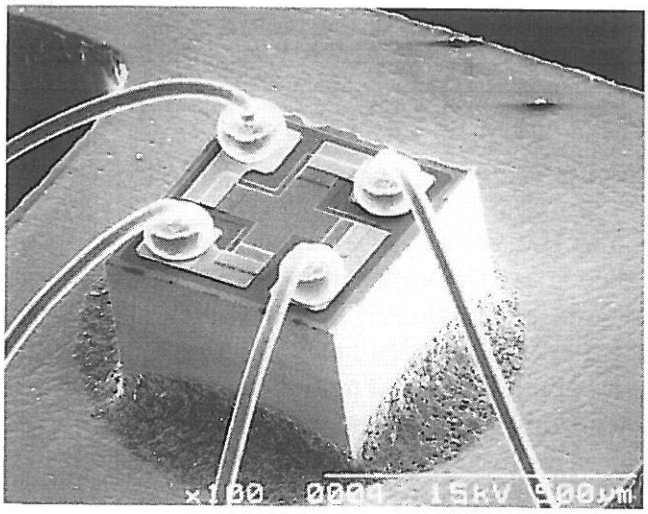

Fig. 6. Photograph of InAs Hall element chip.

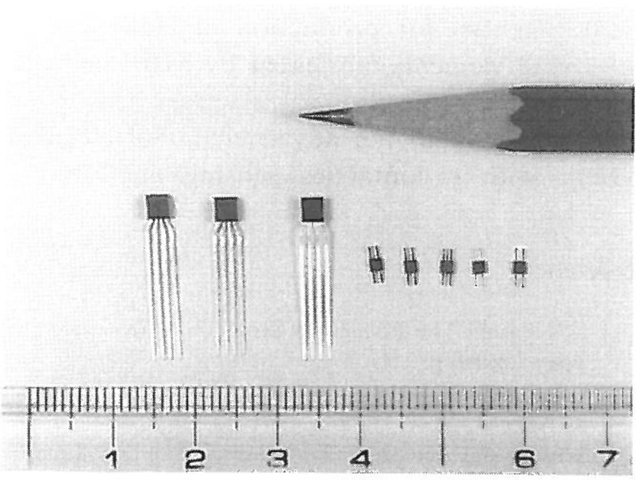

Fig. 7. Photograph of InAs Hall elements fabricated by production MBE.

single crystal because of the large lattice mismatch (~ 7%) between InAs and GaAs. To obtain a higher electron mobility, InAs deep quantum well structures (DQW) have been studied and grown by using a special insulating layer that is lattice matched to InAs by MBE [8–10].

We found a new insulating layer of quaternary material with Sb that has the same lattice constant as InAs and has a large band gap energy of about 1.0 eV a suitable composition that works well as a high potential barrier to form the InAs quantum well. For instance, $Al_xGa_{1-x}As_ySb_{1-y}$ ($0 \leqslant x \leqslant 1$, $0 \leqslant y \leqslant 1$) is a suitable composition range. This layer absorbs many kinds of defects produced by lattice mismatch between the GaAs substrate and the InAs. Moreover, these defects are electrically inactive and the layer acts as an insulating layer, pinning electrically active defects. By using this insulating layer, we can make rather deep quantum wells with a conductive InAs channel layer having a high electron mobility. The typical InAs DQW Hall element structure is shown in Fig. 9. An InAs well of a thickness of 15 nm was used and a structure comprising of GaAsSb(5 nm)/AlGaAsSb(35 nm)/InAs(15 nm)/AlGaAsSb(600 nm)/GaAs was grown by MBE. The DQW had a high electron mobility of 20 000–32 000 $cm^2/V \cdot s$ (row 3 of Table 1) [11, 12]. The typical Hall output voltage from this DQW was 300 mV/(0.05 T $\cdot$ 6 V) (row 3 of Table 2). The InAs DQW Hall element had a high sensitivity and its temperature dependence was very small compared to other kinds of Hall elements (Fig. 8).

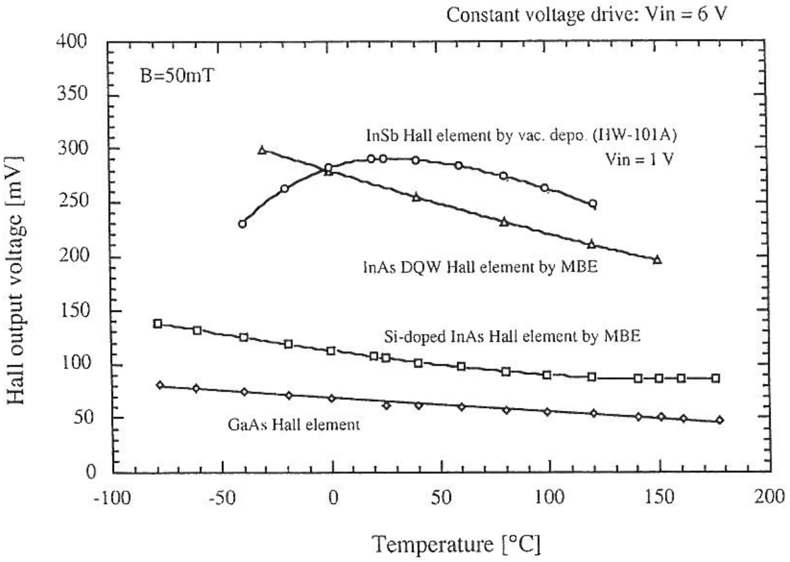

Fig. 8. Temperature dependence of Hall output voltage for various kinds of Hall elements.

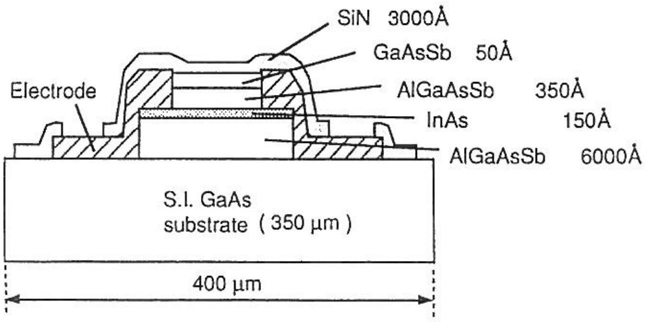

Fig. 9. InAs DQW Hall element (cross-section).

InAs DQW Hall elements hold promise as future magnetic sensors. The InAs DQW is grown uniformly by MBE using a multi-wafer holder with a rotation mechanism. The average electron mobility and sheet carrier density for four 2-in. wafers on one substrate holder grown by MBE are 24 050 $\pm$ 180 $cm^2/V \cdot s$ and $(0.568 \pm 0.008) \times 10^{12}/cm^2$, respectively. We believe InAs DQW Hall elements having high sensitivity and stability in a wide temperature range will be produced by this production MBE in the future. The InAs DQW is applicable to many kinds of sensors and electronic devices. Therefore, MBE technology would be applied to the mass production of many kinds of electronic and sensing devices.

6. Conclusions

The Hall element as a magnetic sensor has established a major application area for III–V compound semiconductor thin films. A production MBE system was designed and applied to produce InAs Hall elements. The high sensitivity and wide operation temperature range characteristics required for future applications of Hall elements were demonstrated in the InAs Hall elements fabricated by MBE. Moreover, many good characteristics for applications have been shown for InAs Hall elements. MBE technology has been shown to have great potential for production of Hall elements. InAs Hall elements fabricated by MBE will open new areas of application for magnetic sensors and will contribute to the advancement of electronic systems with its contactless sensing function.

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