MBE research and production of Hall sensors

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The market for magnetic sensors has been growing rapidly. In 1995, Asahi Kasei Electronics (AKE) commercially produced over 800 million InSb high-sensitivity Hall sensors (which amounts to 70% of the world market) by vacuum deposition. InAs Hall sensors having good noise properties and small temperature dependence have also been developed by mass production molecular beam epitaxy (MBE). Further, InAs deep quantum well (InAs DQW) Hall sensors with high sensitivity and good stability under a wide temperature range are opening up new applications of magnetic sensors. Hall sensors have now become an important application for III-V compound semiconductors.

Hall sensors are a type of semiconductor magnetic sensor mainly used for brushless motors (Hall motors) in such electronic equipment. They detect magnetic fields and generate voltage signals in proportion to the fields called Hall output voltage. Hall sensors typically consist of a rectangular semiconductor thin film on a substrate and four electrodes on the semiconductor film, one pair for input and one pair for output. In recent years, the markets for various electronic equipment such as VCRs, PCs with floppy disk and CD-ROM drives have been growing rapidly. The market for Hall sensors is growing at more than 20% per year due to the explosive growth occurring in the markets for PCs and VCRs.

In 1995, approximately one billion Hall sensors were manufactured worldwide. Due to the need for high sensitivity, 80% of Hall sensors are made of InSb and less than 20% are made of GaAs. Other materials are used in less than 1% of all Hall sensors produced.

Asahi Kasei Electronics (AKE), a wholly-owned subsidiary of Asahi Chemical Industry Co., Ltd, has established itself as a leading manufacturer of Hall sensors. In 1995, over 800 million InSb high-sensitivity Hall sensors (HW series) produced by AKE were used in many applications of magnetic sensors. Amounting to 70% of the world market. AKE also produces magneto-resistors and hybrid-type Hall ICs as well as Hall sensors. Toshiro Isoya, President of AKE, says, “AKE is committed to serving the rapidly expanding market with our highly sensitive Hall sensors having excellent quality and reliability. AKE will also continue to bring innovative products to our customers with leading-edge thin film technology.”

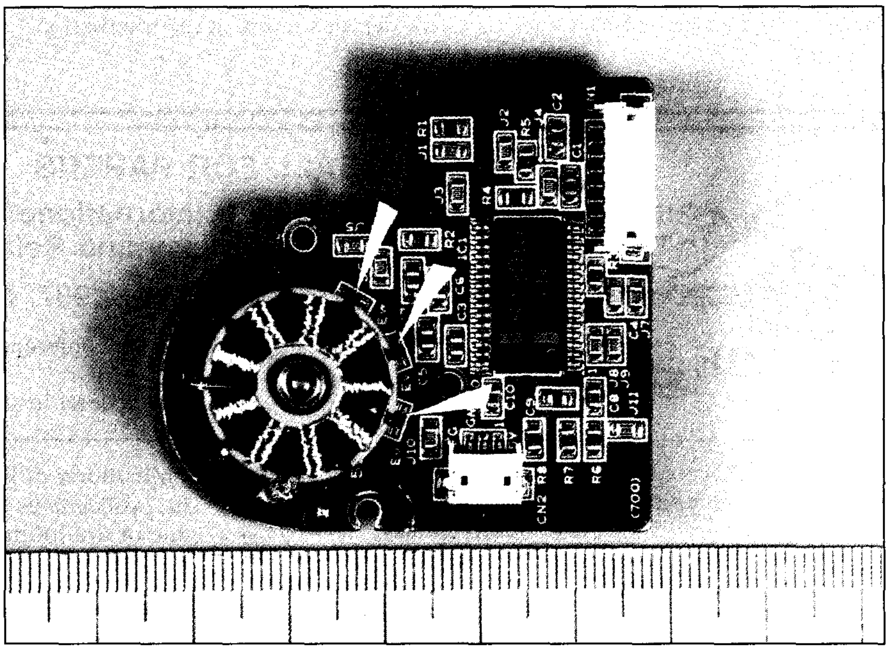
Figure 1. A Hall motor in the CD-ROM drive. Three Hall sensors (white marks) are used.

In this article, we would like to introduce our Hall sensors and take a look at the future of magnetic sensors, focusing on the three types of Hall sensors — InSb, InAs, and InAs deep quantum well (InAs DQW).

Highly sensitive InSb Hall sensors

Since AKE was founded in 1980, we have been producing highly sensitive InSb Hall sensors. InSb polycrystal thin films grown by vacuum deposi-

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Table 1. Performance of InSb high sensitive Hall sensor (HW101A).

1) Hall output voltage at 1V, 0.05T	122~320 mV
2) Input and output resistance	240~550 Ω
3) Offset voltage at 1V, 0T	< ± 7 mV
4) Maximum input voltage	2.0 V
5) Maximum input current	20 mV
6) Operating temperature range	-20~100 °C

Table 2. Hall measurement results of InSb, InAs, InAsDQW at room temperature.

	Doping	Electron mobility (cm²/V·s)	Thickeness (nm)	Electron density (x10^{16}cm^{3})
InSb	non	20000~30000	800	2
InAs	Si	11000	500	8
InAs DQW	non	20000~32000	15	50~90

Table 3. Comparison of InSb, InAs, InAsDQW Hall sensors.

	Driving voltage (V)	Hall output voltage (mV) (B= 0.05 T)	Offset voltage (mV) (B= 0 T)	Input resistance (Ω)
InSb	1	150~320	< ±7	240~550
InAs	6	100	< ± 16	400
InAs DQW	6	250~300	< ± 16	700

tion have a high electron mobility of 20 000 to 30 000 cm^2 V^{-1}s^{-1} and high sheet resistance. These InSb thin films have been applied to highly sensitive Hall sensors with good characteristics, i.e. small size, low cost, high reliability and small temperature dependence of the Hall output voltage in the room temperature range [1].

InSb thin films are grown on thin mica substrates by a vacuum deposition system with multi-evaporation sources. The InSb thin film is peeled off from the mica substrate and bonded on a ferrite substrate. Then the InSb is processed to highly sensitive Hall sensors with magnetically amplified structures. Figure 2 shows a cross-section of an InSb Hall sensor with an InSb thin film sandwiched between the ferrite substrate and a ferrite chip. In this structure, the magnetic field located at the InSb thin film is amplified by the ferrites. The amplified InSb Hall sensors have 3-6 times as high sensitivity as those without ferrites. The advantage of this amplified structure is that it enlarges Hall output voltage without increasing the driving voltage and power consumption. Typical characteristics of the InSb Hall sensors (HW-101A) are shown in Table 1. The InSb Hall sensors have the highest sensitivity, low power consumption and small offset voltage. Moreover, they have stable temperature dependence of Hall output voltage at a constant voltage driving around room temperature.

Figure 3 shows a photograph of commercial InSb Hall sensors, now one of the standard magnetic sensors for DC brushless motor controls. A Hall motor in CD-ROM drive has three Hall sensors, as shown in the lead photograph (Fig. 1). The Hall sensors detect the magnetic field of a rotor made from a permanent magnet to control the rotation speed of the motor. This type of Hall motor is widely used in electronic systems such as VCRs, FD, and CD-ROM drives of personal computers. The market for our highly sensitive InSb Hall sensors is expanding as the production of VCRs and personal computers increases. The only problem with our InSb Hall sensors is the large temperature dependence of their input resistance resulting from the narrow energy band gap of InSb. This limits their use to near room temperature.

InAs thin film Hall sensors by multi-wafer MBE

To make the Hall sensors more stable under a wide temperature range, we started researching and developing InAs thin film sensors in 1982. Bulk InAs single crystals have the second highest electron mobility of 33 000 cm^2 V^{-1}s^{-1} of all III-V compound semiconductors, and an energy band gap twice as large as InSb. However, it is very difficult to grow high-quality InAs thin films because there are no insulating substrates lattice-matched to InAs. For instance, GaAs semi-insulating substrates have a 7% lattice mismatch to InAs. If you grow InAs on GaAs substrate, many misfit dislocations form at the InAs/GaAs interface which degrade the electronic properties of the InAs thin film.

We investigated the MBE growth of 0.5 μm thick InAs films with Si doping on GaAs substrates [2]. The electron mobilities of an undoped InAs thin film and a Si-doped InAs thin film are respectively 9 000 cm^2 V^{-1}s^{-1} and 12 000 cm^{2}V^{-1}s^{-1}. The electron densities are 2.89x10^{16} cm^{-3} for the undoped film and 8.01x10^{16} cm^{-3} for Si-doped film. We found that Si-doped InAs thin films grown by MBE show a higher electron mobility and more stable temperature dependence than undoped films. By using this InAs thin film, we were able to develop InAs Hall sensors that have about 50% higher sensitivity than GaAs Hall sensors and a wider operating temperature range than InSb Hall sensors [2, 3]. InAs Hall sensors are very stable at temperatures exceeding 100°C and low temperature below 0°C. At an electron density of

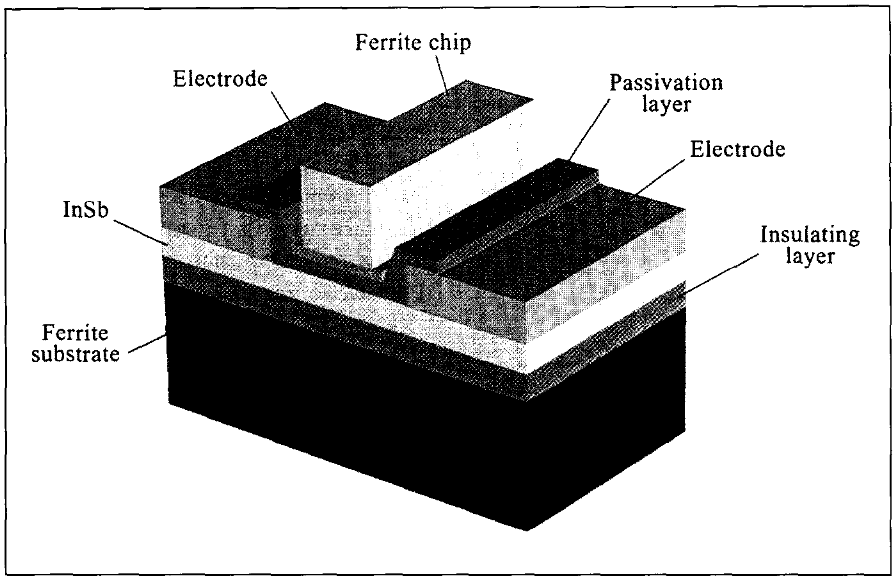

Figure 2. A schematic cross-section of InSb Hall sensor.

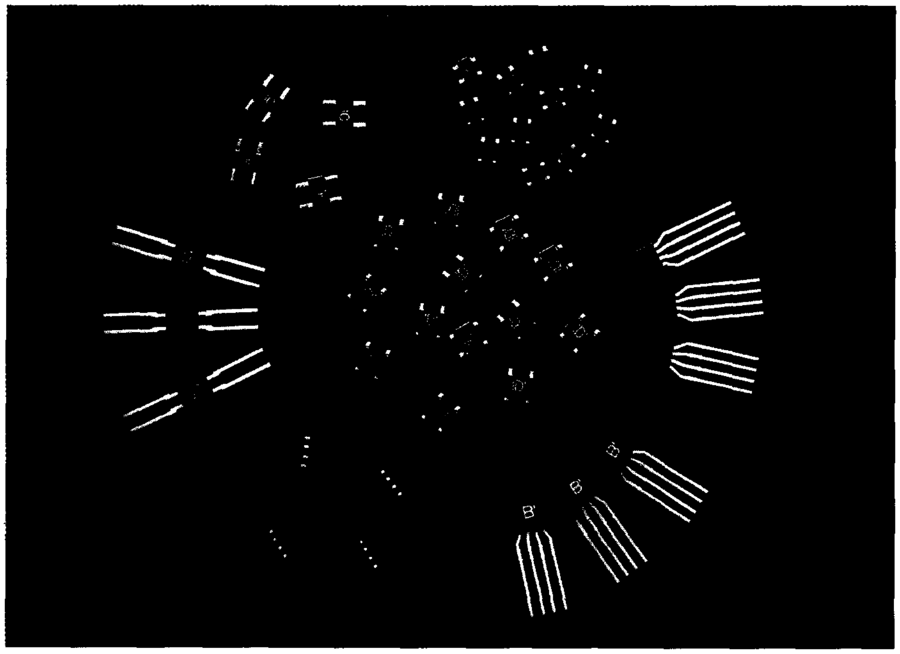

Figure 3. InSb Hall Sensors (HW series).

$8x10^{16}$ cm^{-3} or higher, the temperature coefficient of the input resistance is 0.05%/K around room temperature [3]. Therefore, InAs Hall sensors have characteristics good enough for practical use under wider temperature ranges.

To mass produce InAs Hall sensors, we developed a specially designed MBE system with a multi-wafer substrate holder (twelve 2-inch wafers or five 3-inch wafers). Figure 4 shows our mass production MBE system. To ensure film-thickness uniformity, we optimized the incident beam angle and the distance between sources and substrates. The uniformity of electron-mobility and sheet resistance between inter-wafer is good enough to produce Hall sensors in quantity, as shown in Fig. 5. Our MBE system satisfies high throughput and high yield requirements with excellent reproducibility. InAs Hall sensors have small temperature dependence of output voltage, good stability to pulse voltage noise, low offset drift and low noise properties for low magnetic field sensing. In 1995, about two million of the InAs Hall sensors were used in such equipment as DC current sensors and brushless motors. MBE technology is useful for producing these InAs Hall sensors.

InAs deep quantum well Hall sensors challenge to higher sensitivity

InAs thin films directly grown on GaAs substrates, however, do not have such a high electron mobility as bulk InAs single crystals (33 000 cm^2 V^{-1}s^{-1}). To increase electron mobility of InAs thin films, we investigated InAs DQW structures made from InAs/AlGaAsSb materials [4, 5]. An InAs/AlSb quantum well (QW) system has recently been studied by several groups [6, 7]. Bolognesi *et al.* [7] obtained high mobilities of more than 30 000 cm^2 V^{-1}s^{-1} at room temperature using a nucleation layer, buffer layers as thick as a few microns, and smoothing superlattices. However, InAs/AlSb materials have a disadvantage for use in practical devices because AlSb easily becomes oxidized during the device fabrication process. Moreover, the thickness of InAs QW is limited to within the critical thickness of about 20 nm because of the lattice mismatch between AlSb and InAs.

Accordingly, we proposed a new InAs/AlGaAsSb QW structure in which the InAs layer is sandwiched between quaternary AlGaAsSb barrier/buffer layers [4]. Incorporation of Ga into the barrier/buffer layers suppresses the oxidation of the layers. Furthermore, As was introduced into the barrier/buffer layers for lattice-matching to InAs. InAs DQWs consist of simple four layers, including a sub-micron-thick AlGaAsSb buffer layer, as shown in Fig. 6. They are grown on semi-insulating GaAs (100) substrates in the specially designed MBE system, equipped with elemental Group III and V sources, the latter producing As_4 and Sb_4 beams. We carefully studied the growth conditions for each layer by using reflection high-energy electron diffraction (RHEED) pattern analysis [5], and observed the initial

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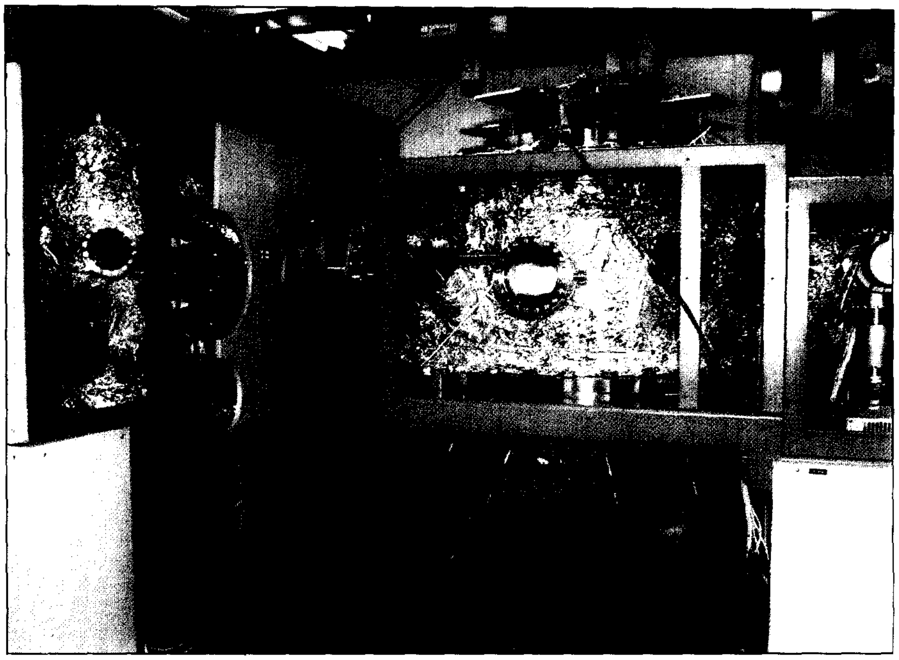

Figure 4. Production MBE system.

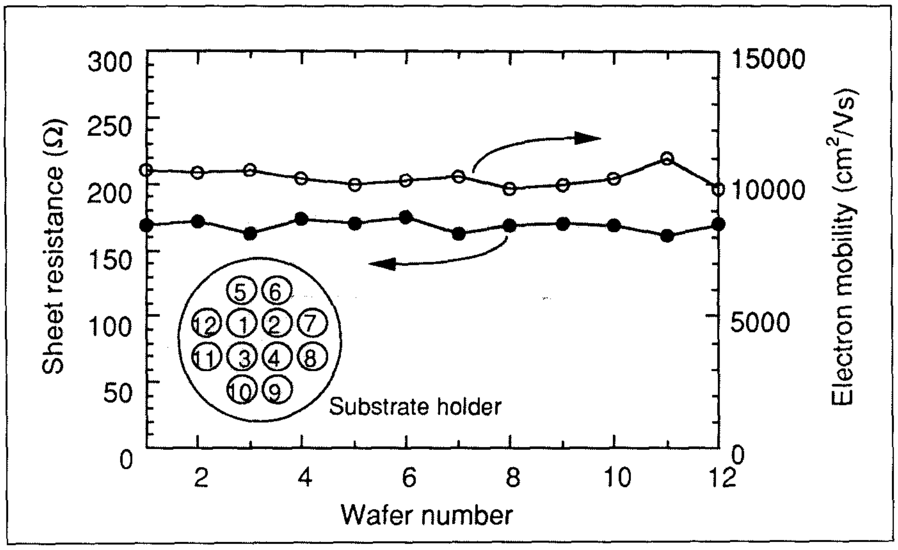

Figure 5. Uniformity of InAs thin films grown by production MBE.

stages of AlGaAsSb growth on GaAs surface and InAs growth on AlGaAsSb surface by atomic force microscopy (AFM) [8]. As a result, we found AlGaAsSb quickly relaxes on GaAs surfaces and plays an important role as an insulating buffer in the InAs DQW. We also confirmed that InAs grows two-dimensionally on AlGaAsSb surface by AFM because AlGaAsSb is lattice-matched to InAs. Furthermore, InAs DQW has a large conduction band offset of ~1.3 eV and can effectively confine electrons in the quantum well. The InAs DQW has a high electron mobility of 20 000-32 000 cm^2 V^{-1}s^{-1}, at room temperature and high carrier density of ~9x10^{17} cm^{-3} in spite of undoped films. We succeeded in growing a 15-nm thick InAs DQW with a maximum electron mobility of 32 000 cm^2 V^{-1}s^{-1}, which is almost the same mobility of InAs bulk. The electrical properties of InAs DQW are summarized in Table 2 and compared with other materials. We also grew four 2-inch wafers simultaneously for mass production of InAs DQWs. High electron mobilities of more than 24 000 cm^{2}V^{-1}s^{-1} have been obtained and can be reproduced. Applying the InAs DQWs to Hall sensors, we obtained a high output voltage of 300 mV/0.05 T.6 V, small dependence of input resistance on temperature and good reliability [5]. The typical characteristics of InAs DQW Hall sensors are tabulated in Table 3 and compared with Hall sensors made from other materials. Figure 7 shows the Hall output voltage of an InAs DQW Hall sensor as a function of temperature at a constant voltage drive. Although the InAs DQW sensors are not amplified, they have almost the same high sensitivity as the InSb Hall sensors amplified by ferrites. InAs DQW Hall sensors have realized the combination of a high sensitivity with small temperature dependence. We believe InAs DQW is a very promising material for opening up new potential applications in the near future.

The future

The market for magnetic sensors has grown rapidly year by year, and will continue to grow well into the 21st Century, expanding into new fields and new applications. Customers now require magnetic sensors that are smaller and thinner, and have higher sensitivity, wider temperature stability and better noise properties. It is a matter of course that lower cost is very important. We will focus on improving our MBE technology from the research stage to the production stage and bring innovative sensors to our customers.

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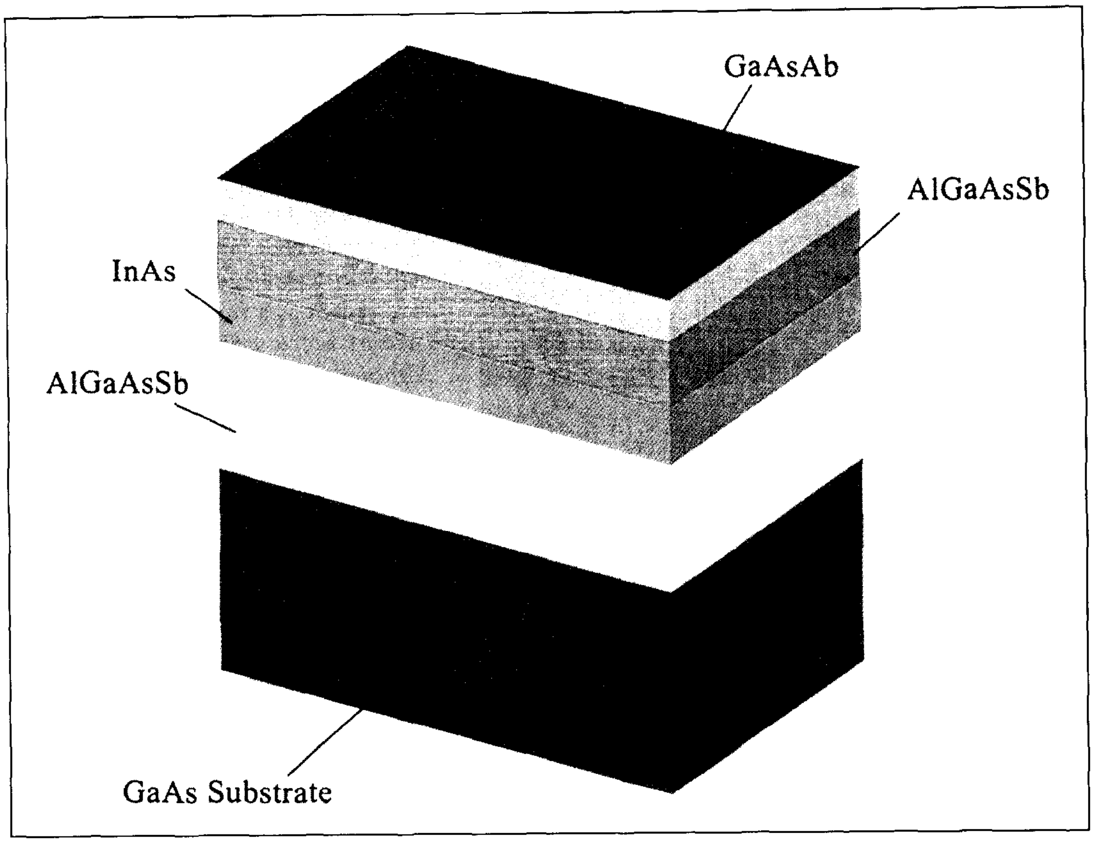

Figure 6. A schematic cross section of InAs DQW.

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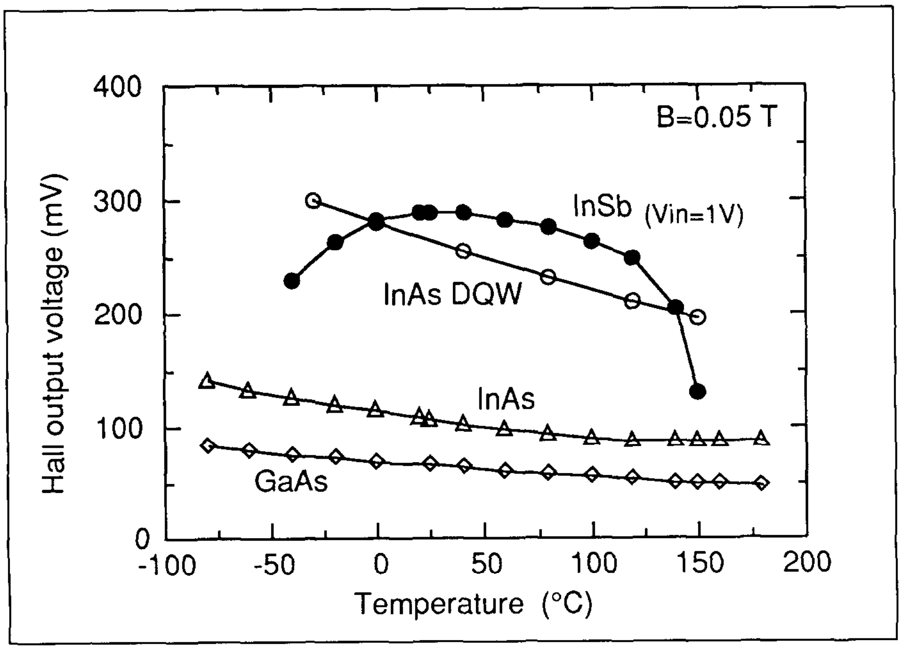

Figure 7. Hall output voltage as a function of temperature at constant voltage drive (V_{in} = 6 V); InSb in magnetically enhanced with ferrite chips, V_{in} -1 V.

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