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Planar Hall effect of indium antimonide thin film on silicon and nickel–zinc ferrite substrates

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Abstracts We have investigated Hall and planar Hall (PH) effect of indium antimonide (InSb) films thermally evaporated on two different substrates including Si and soft magnetic Ni–Zn ferrite. Polycrystalline InSb film with an average grain size of 1.2 μm shows substantial electron mobility of 6,700 cm^2/Vs for Si and 5,680 cm^2/Vs for Ni–Zn ferrite substrates respectively. Four-point bridge type Hall bar of InSb was fabricated using photolithography followed by chemical wet etch. An abrupt change in PH deviated from a normal PH curve was found on a ferrite substrate within a low field range of –50 to 50 Oe while no change happens on the Si substrate. Sharp PH curve immediately returns to the ordinary PH curve when applied field goes over –50 to 50 Oe without leaving any hysteresis of resistance. This is mainly attributed to the presence of the Bloch wall of Ni–Zn ferrite underneath InSb Hall bar. Intragranular domain wall movement is believed to be a prime source of the anomalous PH behavior in the low field range. The linear field dependence of PH in a resolution of 10 mΩ/Oe is sensitive high enough to be used as low-field magnetic sensors.

Introduction

InSb semiconductors have been regarded as a promising candidate for various sensors such as infrared detectors and Hall sensors because of its high room-temperature mobility and narrow energy band gaps [1]. Especially, high magnetoresistance (MR) of InSb resulted from an ideal combination of ordinary MR (OMR) and extraordinary MR (EMR) makes it attractive for read-head sensors for ultra-high-density magnetic recording [2, 3].

Recently, a lot of efforts have been made to improve the crystal quality of InSb thin film fabricated with molecular beam epitaxy (MBE) [4] and metal organic chemical vapor deposition (MOCVD) [5], and to stabilize temperature dependence of Hall sensitivity by a suitable control of doping concentration [6]. Hall mobility of monocrystalline of InSb grown by MBE was reported to reach an order of 27,000 cm^2/Vs at room temperature [4].

InSb thin films prepared by thermal evaporation method on a sintered Ni–Zn ferrite substrate have been used for commercially available Hall sensor owing to low cost and simple process for the mass production. The use of ferrite as a flux gate turns out to be very effective to increase Hall sensitivity because large permeability of the ferrite greatly enhances applied magnetic field [1].

In the study, we have carefully measured Hall and PH effect of polycrystalline InSb Hall bar on (100) monocrystalline Si and polycrystalline Ni–Zn ferrite and found an intriguing change in PH only on a ferrite substrate. This anomalous PH was observed in a low field range from ±50 Oe with a sensitivity of 10 mΩ/Oe. The PH on the peak immediately returns to the ordinary PH curve without leaving the hysteresis of resistance when applied field exceeding over ±50 Oe. The origin of this unusual PH behavior of InSb on ferrite substrate is believed that the movement of Bloch wall in polycrystalline Ni–Zn ferrite under in-plane field condition is a prime source of the anomalous change of PH in a specific field range.

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Experiments

Prior to the evaporation of InSb, 200 nm thick SiO_2 insulating layer was first deposited on Si substrate by plasma enhanced chemical vapor deposition process. About 0.9 μm thick InSb film was deposited on oxidized (100) Si and polycrystalline Ni–Zn ferrite substrates by thermal evaporator. The bulk InSb crystal was used for source material of the evaporation. Substrate and source material were heated up to 400 °C and 800 °C respectively in a vacuum chamber of 5×10^{-6} Torr during the deposition. Scanning electron microscopy (SEM, JEOL 6500F) and X-ray diffractometer (Philips X'pert) were used to investigate microstructure and crystal characterization of deposited InSb thin film. For Hall effect measurements, as-grown InSb film was patterned into a four-point bridge type Hall bar where the cross junction is 3×3 μm^2 using photolithography followed by chemical wet etch. Then, Ti/Au electrodes for electrical contact pad and leading wires were fabricated by lift-off process. For a thin film with in-plane magnetic field, MR measurements are usually performed using a conventional four-terminal technique, in other words, the voltage is measured from the *a–b* leads and the current is measured from the *c–d* leads (Fig. 1).

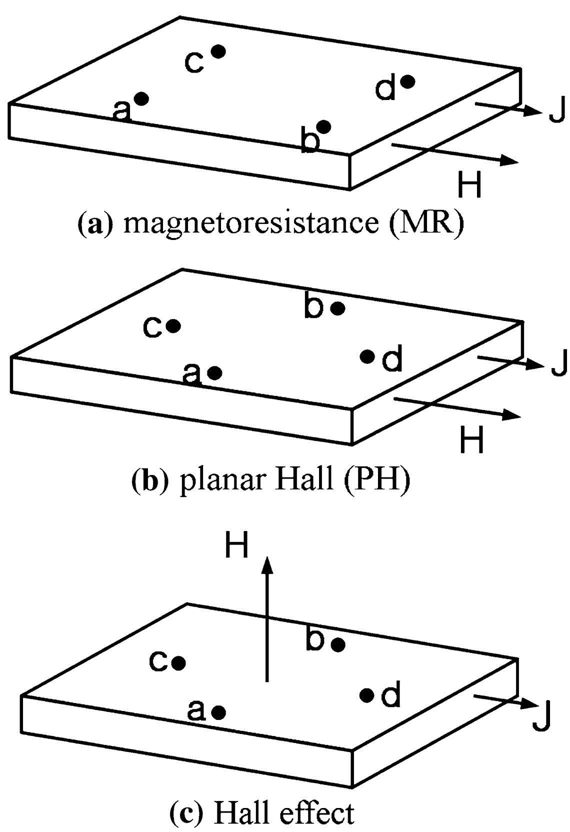

Fig. 1 Conventional four probe arrangements of resistance measurement are shown schematically. Thin film with the relative directions of current density (J) and applied magnetic field (H)

Several current–voltage configurations are often studied: The parallel current–voltage configuration is usually defined as magnetoresistance (MR) (Fig. 1a) and the perpendicular current–voltage configuration through Hall bar is often called planar Hall (PH) (Fig. 1b) [7]. Figure 1c shows a typical Hall effect measurement. Conventional four-probe ac magneto-transport measurement was made on these devices using physical property measurement system (PPMS, Quantum design) at room temperature while an in-plane field was swept over roughly ±500 Oe at room temperature. Magnetic hystresis curve was obtained with vibrating sample magnetometer (AGM, Princeton Measurement Corporation MicroMag 2900) and magnetic domains of Ni–Zn ferrite substrate was investigated with magnetic force microscopy (MFM, Seiko SPA-400).

Results and discussion

Top-view SEM image of thermal evaporated InSb thin film can be seen in Fig. 2. The thermal evaporation process readily produces polycrystalline InSb film whose mean grain size was measured to about 1.2 μm. Polycrystalline thin film is usually suffered from high surface roughness which probably causes poor electrical contact with metal, but root mean square (rms) of the film investigated by AFM is estimated around 30 nm which allows a good electrical contact.

Hall measurement was made on both samples at room temperature in order to assess an intrinsic quality of InSb film deposited on different substrates. Figure 3 shows Hall (a) and PH resistance (b) of both substrates as a function of applied magnetic field. Hall and PH gradients of each substrate are summarized in Table 1. Hall mobility and carrier concentration were calculated to 6,700 cm^2/Vs and

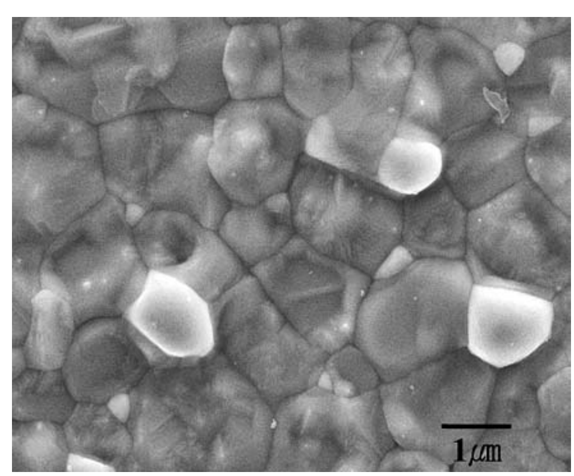

Fig. 2 Top-view SEM image of thermally evaporated 0.9 μm thick InSb thin film on Si substrate

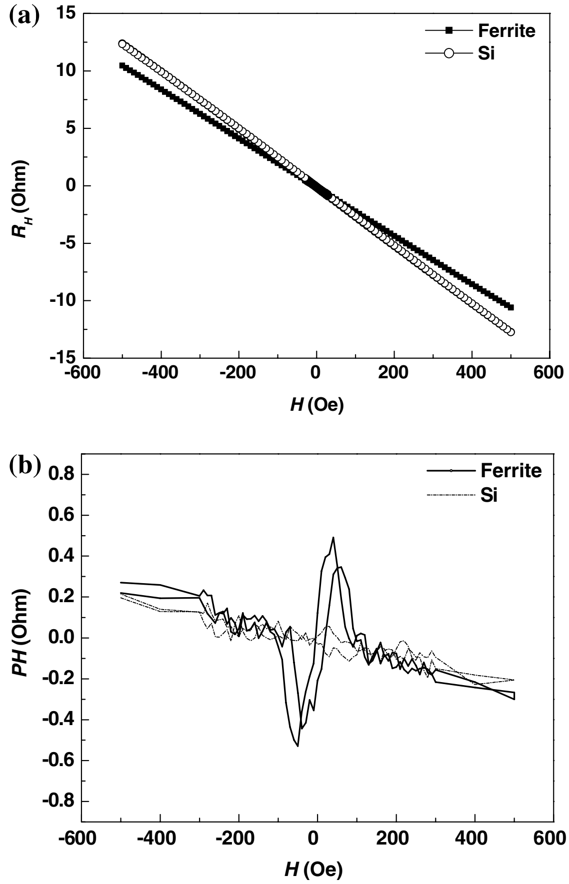

Fig. 3 Hall resistance (**a**) and planar Hall (PH) resistance (**b**) at room temperature as a function of magnetic field for the InSb Hall bars on two different substrates Si and ferrite

$1.3 \times 10^{16}/cm^3$ for Si and 5,680 cm^2/Vs, $3.3 \times 10^{16}/cm^3$ for Ni–Zn ferrite substrates respectively. Lower electron mobility of InSb on a ferrite substrate is probably due to the interference of enhanced magnetic field by a magnetic ferrite substrate. Although Hall mobility of polycrystalline InSb appears to be lower than that of MBE grown InSb films [4], it still has substantial mobility high enough to be used as Hall sensors.

Unlike Hall resistance in Fig. 3a, a significant change in PH was found only on a ferrite substrate while little change on a Si substrate. This anomalous PH behavior in a ferrite substrate occurs in a low field range of ±50 Oe showing a linear field sensitivity of 10 mΩ/Oe. The anomalous increase in PH immediately returns to the ordinary PH curve without leaving any magnetic hysteresis when applied field exceeding over the field of ±50 Oe. It is evident that the sharp change in PH is entirely caused by the influence of magnetic field coming out of a ferrite substrate underneath the Hall cross of InSb because no change in PH curve was observed on a Si substrate.

The magnetoresistance (MR) of Hall bar when applying in plane field has been studied by Johnson et al. They employed the fringe field from an edge of a ferromagnet to increase the Hall voltage [8, 9]. They clearly showed the hysteresis loop resulting from the fringe field of ferromagnet and saturation of MR approximately at a coercive field of an upper ferromagnet. For our device, the fringe field effect from both edges of soft ferrite can be negligible because the edge of ferrite substrate is far away from the Hall cross.

Table 1 Measured Hall gradient of InSb thin film deposited on two different substrates

	Substrate	Hall gradient ΔR_H (Ω/Oe)
Hall	Si	0.025
	Ferrite	0.02
PH	Si	0.0004
	Ferrite	–50 ≤ H≤ 50 0.015
		H ≥ 50, H ≤ –5 0.0004

Figure 4 shows representative hysteresis loops for Ni–Zn ferrite, obtained with applied magnetic field parallel to the film at room temperature. The typical soft magnetic hysteresis of the ferrite can be seen in the inset, indicating that the coercive field (Hc) and saturation magnetization (Ms) of Ni–Zn ferrite are 20 Oe and 4 emu/cc, respectively.

Microstructure and magnetic domains of Ni–Zn ferrite were investigated with AFM and MFM (Fig. 5). The AFM and MFM image were obtained in the same place of a ferrite near InSb Hall cross in zero external field. The average grain size of Ni–Zn ferrite substrate was measured to 6 μm by mean linear intercept method from AFM observation. The MFM image (phase channel, tapping mode) shows 1 μm wide, 4 μm long magnetic domains. According to the literature, the domain size of Ni–Zn ferrite is directly dependent on the grain size. The ratio between domain and grain size of the ferrite corresponds to 0.63 for two domain states [10]. The observation in Fig. 5 clearly tells that every single grain of a ferrite statistically contains several magnetic domains separated by Bloch domain walls. It means that at least five domains in the ferrite exist underneath InSb Hall cross because the area of Hall cross is 5 × 5 μm^2. If in-plane field was applied to the ferrite, the domains aligned with a field increase as the domain wall moves along the field direction, and the pole density at the domain wall linearly increases.

From the experimental results, it is postulated that the origin of anomalous change in PH on a ferrite substrate is associated with the motion of Bloch wall in a low field range. Typical soft magnetic characteristics of Ni–Zn ferrite is supported by a lot of magnetic domains with rapidly movable Bloch domain walls [10, 11]. As can be illustrated in Fig. 6, if the preferred axis of a ferrite is oriented parallel to the surface and if the anisotropy is sufficiently

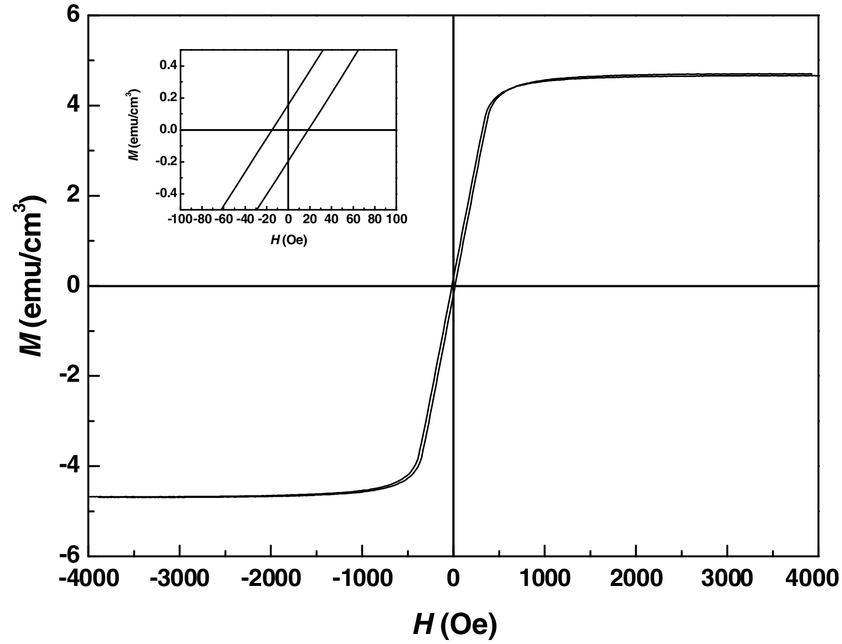

Fig. 4 Magnetic hysteresis loop of Ni–Zn ferrited on which InSb thin film was deposited

strong, Bloch walls are easily formed between two magnetic domains. Since Bloch walls carry some magnetic flux, the magnetic field lies perpendicular to the surface in the walls [12]. If some Bloch walls are located underneath the InSb Hall cross at in-plane magnetic field, the PH of InSb may be locally affected by the perpendicular magnetic field from the Bloch wall. From the observation, we can estimate that 5×5 μm^2 square Hall cross of InSb statistically covers at least 5 magnetic domains separated by Bloch walls because Ni–Zn ferrite has 1 μm long and 4 μm wide magnetic domains. In a low field range of ±50 Oe, electron transport through InSb Hall cross is subjected to change under not in-plane but perpendicular magnetic field coming out of Bloch walls and therefore, it follows the similar behavior of conventional Hall gradient. Actually, PH gradient of ferrite is determined to 0.015 Ω/Oe in the range of ±50 Oe which is almost identical to its Hall gradient of 0.02 Ω/Oe. (Table 1) By contrast, PH gradient of ferrite (0.0004 Ω/Oe) in the high field over ±50 Oe is much lower than its Hall gradient but appears exactly the same to PH of Si substrate (0.0004 Ω/Oe). It means that perpendicular field acts on a ferrite substrate in the low field range and the field completely disappears when magnetic field increases over the critical field of 50 Oe. We believe that the anomalous PH behavior found on a ferrite substrate is originated from the Bloch wall motion. As the field increases in the low field range, Bloch walls start to move gradually at the initial stage and finally move away from the Hall cross corresponding to the soft magnetization of ferrite. When ferrite is getting magnetized, no Bloch walls remain underneath the InSb Hall cross and they do not provide perpendicular field to the InSb any more so that the resistance drastically changes to the ordinary PH curve. Therefore, the results demonstrate that PH is sensitive high enough to determine the local magnetic field from Bloch walls. The advantage of its high sensitivity was already suggested by the theoretical study [7]. The linear field response of PH in low magnetic field is well suited for the application as a low magnetic field sensor with a resolution of 10 mΩ/Oe.

Conclusion

In summary, we have investigated the Hall and PH behavior of InSb thin film grown on non magnetic Si and soft magnetic Ni–Zn ferrite and found an anomalous PH feature of InSb on a Ni–Zn ferrite in a low field range of –50 to 50 Oe. This drastic change in PH of ferrite substrate has a linear dependence of 10 mΩ/Oe in the field range. It also has a unique feature that PH immediately returns to the ordinary PH curve without leaving the hystresis of PH resistance when applied filed exceeding over the field range. This is mainly attributed to the presence of the Bloch walls, which is a source of local perpendicular magnetic field directly influencing the electron transport of upper InSb Hall bar. Intragranular Bloch wall movement is believed to be the prime origin of the anomalous PH behavior in the low field. The anomalous PH behavior of polycrystalline InSb films on a ferrite substrate demonstrating a linear field response in low magnetic field is well suited for application as a low field magnetic sensor.

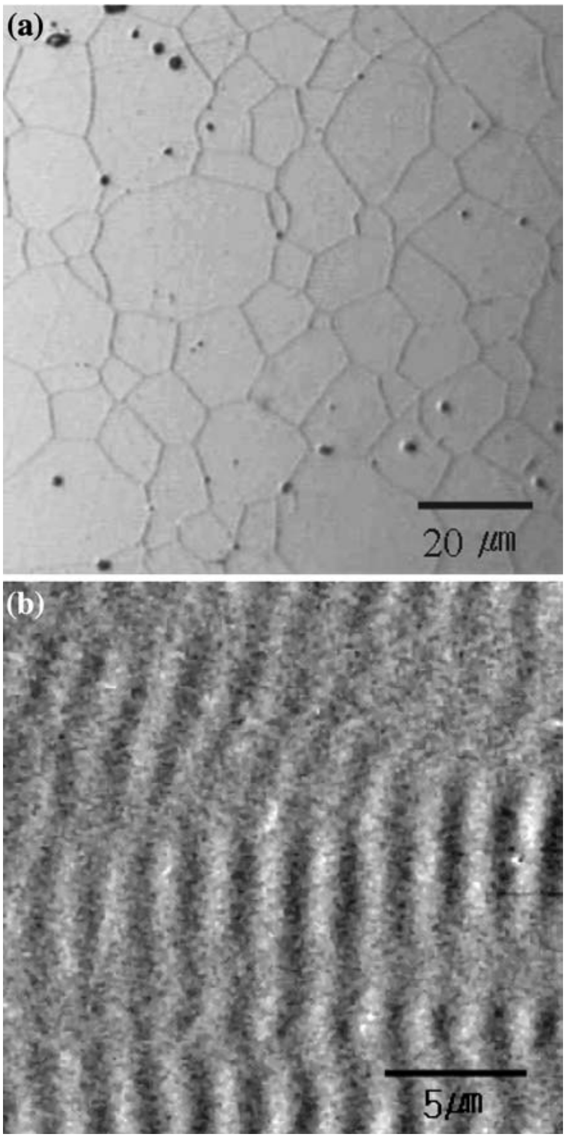

Fig. 5 AFM topography and MFM image of 20 μm by 20 μm Ni–Zn ferrite in zero applied field

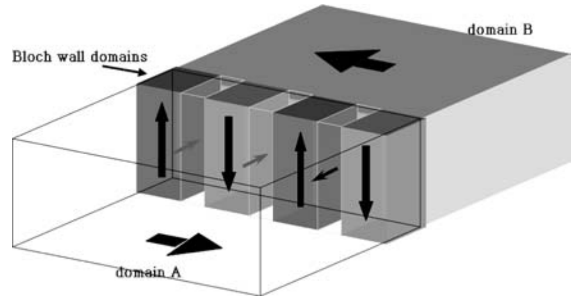

Fig. 6 Schematics of Bloch wall structure between two in plane magnetized magnetic domains in a ferrite substrate and origin of the fringe field perpendicular to the surface

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