High sensitivity and multifunctional micro-Hall sensors fabricated using InAlSb/InAsSb/InAlSb heterostructures

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Further diversification of Hall sensor technology requires development of materials with high electron mobility and an ultrathin conducting layer very close to the material's surface. Here, we describe the magnetoresistive properties of micro-Hall devices fabricated using InAlSb/InAsSb/InAlSb heterostructures where electrical conduction was confined to a 30 nm-InAsSb two-dimensional electron gas layer. The 300 K electron mobility and sheet carrier concentration were 36 500 $cm^2 V^{-1} s^{-1}$ and 2.5×10^{11} cm^{-2}, respectively. The maximum current-related sensitivity was 2 750 $V A^{-1} T^{-1}$, which was about an order of magnitude greater than AlGaAs/InGaAs pseudomorphic heterostructures devices. Photolithography was used to fabricate 1 μm $\times 1$ μm Hall probes, which were installed into a scanning Hall probe microscope and used to image the surface of a hard disk. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3074513]

I. INTRODUCTION

Hall effect magnetic field sensors are ubiquitous. Applications include monitoring the rotation of mechanical parts in electronic equipment and measurement of electric currents in power cables. Further, micro-Hall sensors have also been used for novel applications including scanning Hall probe microscopy (SHPM) of ferromagnetic domains[1–3] and as biosensors for the detection of superparamagnetic particles for biorecognition.[4,5]

Future room temperature applications of Hall sensor technology require development of materials exhibiting high electron mobility and ultrathin conducting layers close to the material's surface. For a fixed device size and geometry, the magnetic field sensitivity of Hall sensors scales with the electron mobility and nanometer-scale conduction channels are important for forming submicron devices.[6]

Here, we describe the magnetoresistive properties of micro-Hall devices fabricated using InAlSb/InAsSb/InAlSb quantum well (QW) heterostructures grown by molecular beam epitaxy.[7] Electrical conduction was confined to a two-dimensional electron gas (2DEG) layer in the 30 nm InAsSb. The room temperature electron mobility and sheet carrier concentration were 36 500 $cm^2 V^{-1} s^{-1}$ and 2.5 $\times 10^{11}$ cm^{-2}, respectively. The current-related sensitivity of Hall devices was 2 750 $V A^{-1} T^{-1}$, which is about an order of magnitude greater than AlGaAs/InGaAs pseudomorphic device structures. We compare the performance of InAlSb/InAsSb/InAlSb heterostructure Hall sensors with AlGaAs/InGaAs devices and demonstrate the exceeding potential of the former by using a scanning Hall probe microscope to image localized magnetic fields at the surface of a hard disk.

II. EXPERIMENTS

The InAlSb/InAsSb/InAlSb heterostructures were grown using molecular beam epitaxy on semi-insulating (100) GaAs substrates. An insulating layer of 600 nm InAlSb was first grown on the substrates, followed by the deposition of 30 nm undoped InAsSb active layer, 55 nm InAlSb layer, and 6.5 nm of insulating GaAs as a protection layer.

The fabrication process involved (1) formation of the active "cross" area using a combination of photolithography and wet chemical etching; (2) deposition of AuGe Ohmic contacts by vacuum evaporation as described before;[8] and (3) thermal annealing in a nitrogen atmosphere at 600 K for 3 min.

The Hall mobility and sheet carrier concentrations were determined by the van der Pauw method and noise measurements carried out using digital sampling oscilloscope and fast Fourier transform (FFT) analyzer.[9] Magnetic imaging was carried out by mounting InAlSb/InAsSb/InAlSb micro-Hall probes into a scanning Hall probe microscope system to observe the magnetic domains on the surface of a hard disk.[10]

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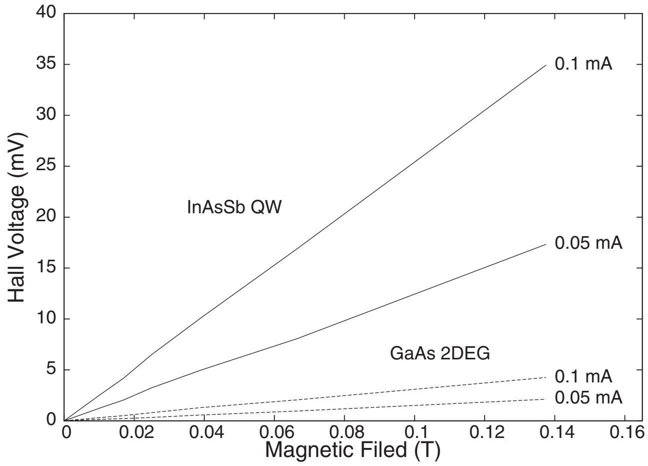

FIG. 1. 300 K Hall voltage of InAlSb/InAsSb/InAlSb and AlGaAs/InGaAs as a function of the applied magnetic field for several driving currents.

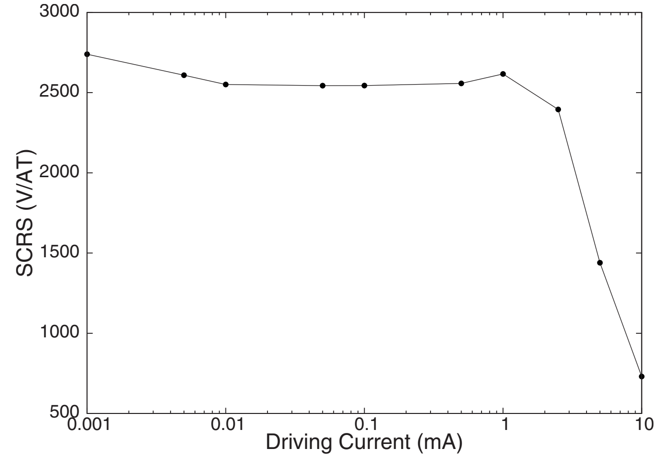

FIG. 2. The SCRS as a function of the driving current for InAlSb/InAsSb/InAlsb at 300 K.

III. RESULTS AND DISCUSSIONS

The room temperature electron mobility and the sheet carrier density of a InAlSb/InAsSb/InAlSb heterostructure with a 30 nm InAsSb layer were 36 500 $cm^2\ V^{-1}\ s^{-1}$ and $2.5\times10^{11}\ cm^{-2}$, respectively. Further, the Hall voltage was extremely linear for bias magnetic fields up to 0.14 T. Figure 1 is a comparison of the variation in the Hall voltage with magnetic field for AlGaAs/InGaAs 2DEG and the antimonide heterostructures with identical geometry. The results showed excellent linearity.

The absolute sensitivity S_A and the supply-current-related sensitivity (SCRS) S_I of a cross-shaped Hall sensor can be expressed as follows:

$$S_A \equiv \frac{dV_H}{dB}(\mathrm{V\ T^{-1}}), \tag{1}$$

$$S_I \equiv \frac{1}{I_D}\frac{dV_H}{dB} = \frac{1}{n_s e}(\mathrm{V\ A^{-1}\ T^{-1}}), \tag{2}$$

where V_H is the Hall voltage, B is the applied external magnetic field, I_D is the driving current, and n_s is the sheet carrier concentration. From Eq. (2) it can be seen that SCRS depends on the sheet carrier concentration. At moderate driving currents the SCRS for InAlSb/InAsSb/InAlSb was as high as 2750 $\mathrm{V\ A^{-1}\ T^{-1}}$, whereas AlGaAs/InGaAs with a typical n_s of $2.0\times10^{12}\ cm^{-2}$ had 310 $\mathrm{V\ A^{-1}\ T^{-1}}$. Figure 2 shows the supply-current-related sensitivity as a function of driving current I_D. As implied by Eq. (2), the driving current versus the SCRS serves as a monitor of carrier fluctuations caused by thermal or electrical activation processes.[6] Our results show negligible carrier fluctuations thus, S_I was constant at moderate driving currents. The decrease in SCRS at $I_D > 1$ mA indicates the excessive driving current causes thermal carrier activation.[6]

The noise spectra of InAlSb/InAsSb/InAlSb Hall sensors were measured using a FFT signal analyzer at sampling rate of 6.25 Hz for a range of drive current. The minimum detectable magnetic field using a Hall sensor can be expressed as

$$B_{\min} = \frac{V_{\text{noise}}}{S_I I_D}. \tag{3}$$

The noise spectra were measured at I_D=10, 50, and 100 μA. Table I shows the minimum detectable magnetic field of InAlSb/InAsSb/InAlSb and AlGaAs/InGaAs at the aforementioned driving currents and frequencies of 1 and 100 kHz. The results show the magnetic field resolution of InAlSb/InAsSb/InAlSb devices to be about five to ten times better than that of AlGaAs/InGaAs heterostructure Hall sensors. The results can be explained by the high SCRS which results from the low sheet carrier concentration of the antimonide heterostructures as implied from Eq. (2) and low series resistance of InAlSb/InAsSb/InAlSb devices. The series resistance of InAsSb QW and GaAs 2DEG were 1.6 and 3.0 kΩ, respectively. Assuming the Johnson noise $V_n = \sqrt{4k_B TR\Delta f}$ to be the main noise component in the Hall sensor, where k_B, T, R, and Δf are the Boltzmann's constant, temperature, series resistance of the device, and the measurement bandwidth, respectively; Eq. (3) yields the minimum detectable field of InAlSb/InAsSb/InAlSb at I_D=100 μA to be 0.51 $\mathrm{mG}/\sqrt{\mathrm{Hz}}$ which agrees with the measured magnetic field resolution.

The InAlSb/InAsSb/InAlSb heterostructures were used to fabricate micro-Hall probes for use in a scanning Hall probe microscope.[10] Figure 3(a) is a scanning electron microscope image of a typical Hall probe, where the active cross is $1\times1\ \mu m^2$.

Figure 3(b) shows an SHPM image of the surface of a hard disk measured with I_D=500 μA at room temperature.

TABLE I. The magnetic field resolutions of InAlSb/InAsSb/InAlSb and AlGaAs/InGaAs at 1 and 100 kHz.

	Magnetic field resolution ($\mathrm{mG}/\sqrt{\mathrm{Hz}}$)			
	1 kHz		100 kHz	
I_D (μA)	InAsSb QW	GaAs 2DEG	InAsSb QW	GaAs 2DEG
10	6.5	56	0.54	2.5
50	1.1	7.91	0.072	0.49
100	0.58	4.83	0.052	0.30

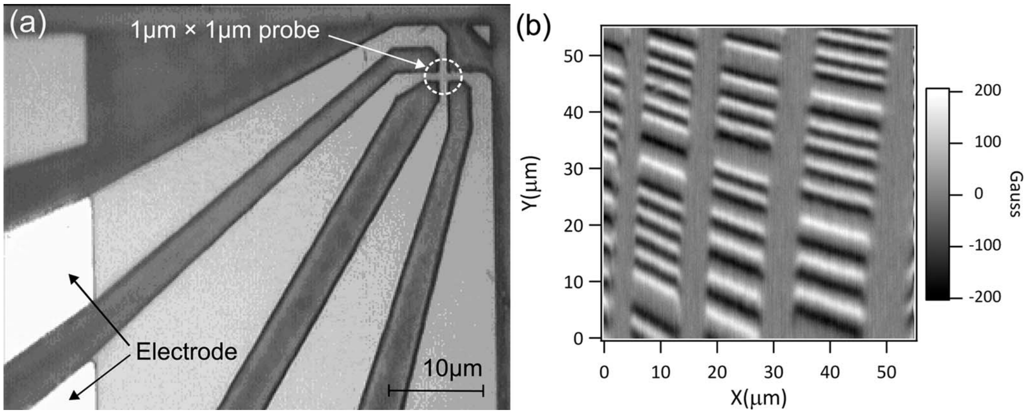

FIG. 3. (a) A typical InAlSb/InAsSb/InAlSb Hall probe with an active area of about 1×1 μm^2 Hall used for magnetic imaging with a scanning Hall probe microscope. (b) SHPM 50×50 μm^2 magnetic image of a hard disk measured using 1×1 μm^2 InAlSb/InAsSb/InAlSb Hall probe. The magnetic field scale from black to white is ±200 G.

The image is 50×50 μm^2 and the gray scale shows the magnetic field variations of ±200 G. The hard disk had striped magnetic domains in which the moment is oriented perpendicular to the surface and each magnetic bit was clearly resolved and detected.

IV. CONCLUSIONS

High mobility InAlSb/InAsSb/InAlSb heterostructures with 2DEG only about 60 nm from the material's surface were used to fabricate micro-Hall sensors. The room temperature figures of merit of the devices were better than GaAs-based Hall sensors with a current sensitivity of 2750 $V\ A^{-1}\ T^{-1}$, which was an order magnitude greater than conventional GaAs 2DEG Hall sensors. The InAlSb/InAsSb/InAlSb were used to fabricate micro-Hall probes and the surface of a hard disk was imaged by SHPM. Future experiments include fabrication of sub-100 nm Hall probes for SHPM imaging and fabrication of Hall biosensors for detection of superparamagnetic particles in biorecognition platforms.

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