Room-Temperature Scanning Hall Probe Microscope (RT-SHPM) Imaging of Garnet Films Using New High-Performance InSb Sensors

A. Oral, M. Kaval, M. Dede, H. Masuda, A. Okamoto, I. Shibasaki, and A. Sandhu

***Abstract*—High-performance InSb micro-Hall sensors were fabricated by optical lithography and incorporated in a room-temperature scanning Hall probe microscope for imaging of localized magnetic fluctuations in close proximity to the surfaces of crystalline uniaxial garnet films. The room-temperature noise figure of the InSb sensors was 6–10 mG/$\sqrt{}$Hz, which is an order of magnitude better than GaAs–AlGaAs two-dimensional electron gas sensors used to date.**

***Index Terms*—Hall effect, scanning Hall probe microscopy.**

I. INTRODUCTION

SCANNING Hall probe microscopy (SHPM) [1] is a quantitative and noninvasive technique for imaging localized surface magnetic field fluctuations such as ferromagnetic domains with high spatial and magnetic field resolution of ~120 nm and 70 mG/$\sqrt{}$Hz, respectively, at room temperature. This new technique offers advantages and complements the other magnetic imaging methods like magnetic force microscopy (MFM) [2], magnetic near field scanning optical microscopy[3], and Kerr microscopy [4]. In SHPM, a submicrometer Hall probe is scanned over the sample surface to measure the perpendicular component of the surface magnetic fields using conventional scanning tunneling microscopy (STM) positioning techniques as shown in Fig. 1. The SHPM system can be designed to enable operation over a wide temperature range (4 K–300 K), and we have previously reported on the excellent properties of GaAs–GaAlAs two-dimensional electron gas (2DEG) Hall probes for cryogenic and room-temperature measurements [5], [6]. In an attempt to overcome Hall sensor drive current limitations due to carrier depletion effects in submicrometer GaAs–AlGaAs 2DEG probes at room temperature, we recently fabricated bismuth (Bi) nano-Hall sensors using focused ion beam milling and achieved a spatial resolution of 120 nm [7]. However, the minimum detectable magnetic field with the Bi nano-Hall sensors was high due to high carrier concentration and low mobility at the room temperature. A promising alternative material for fabricating submicrometer Hall sensors is InSb, which has both of the desired properties (i.e., low carrier concentration and high mobility) at room temperature compared to GaAs–AlGaAs 2DEG and Bi thin films. In this paper, we report on the development of new low-noise, high-performance InSb thin film micro-Hall sensors for room-temperature scanning Hall probe microscopy (RT-SHPM) exhibiting a noise level of 6–10 mG/$\sqrt{}$Hz, which is an order of magnitude better than GaAs–AlGaAs 2DEG sensors.

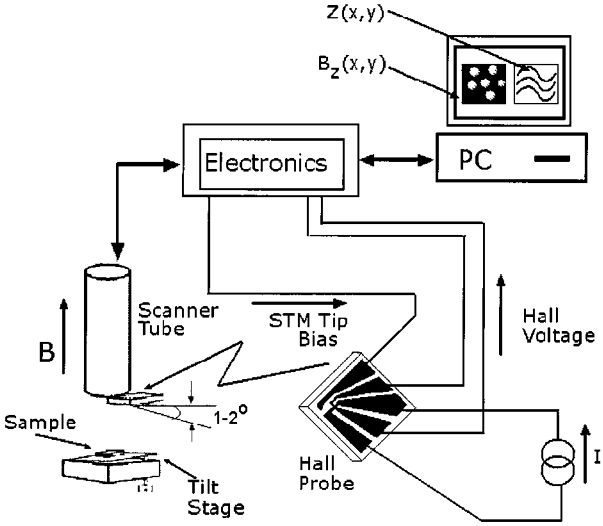

Fig. 1. Schematic diagram of RT-SHPM.

II. EXPERIMENT

A. Scanning Hall Probe Microscope

The RT-SHPM [8] used in this study has a scan range of 50 × 50 μm in XY directions and 4.8 μm in Z direction. The SHPM incorporates XYZ motors for coarse micropositioning, a video camera for Hall sensor alignment, and an integrated coil concentric to the Hall sensor head for the application of external magnetic fields of up to ±40 Oe. Furthermore, a newly developed compact sized powerful pulse coil can be coupled with the system to apply external fields up to ±25 000 Oe. The Hall sensor is positioned close to a gold-coated corner of a deep etch mesa, which serves as STM tip. The Hall probe chip is tilted ~1.25° with respect

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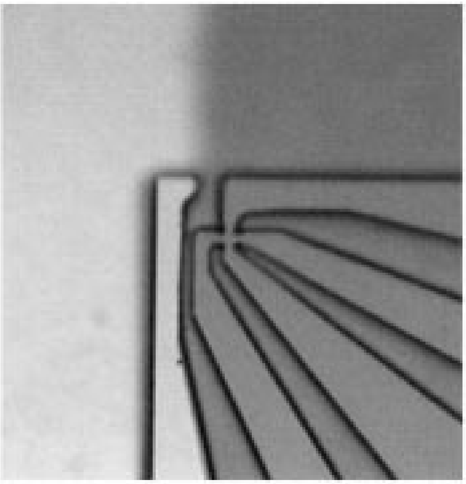


Fig. 2. Optical micrograph of a finished InSb thin film Hall probe. Gold-coated corner of the chip on the left of Hall cross serves as STM tip.

to sample ensuring that the corner of the mesa is the highest point. The microscope can be run in two modes: STM tracking and liftoff mode. In the STM tracking mode, the tunnel current between the corner of the Hall sensor chip and the sample is measured and used to drive the feedback loop enabling the simultaneous measurement of both STM topography and the magnetic field distribution of the sample surface. This mode of operation gives the highest sensitivity because of the smallest probe-sample separation but with the drawback of being slow. In the liftoff mode, the Hall sensor is lifted off to a certain height above the sample and the head can be scanned extremely fast (~4 s/frame) for measurements of the local magnetic field distribution.

B. InSb Hall Probe Microfabrication

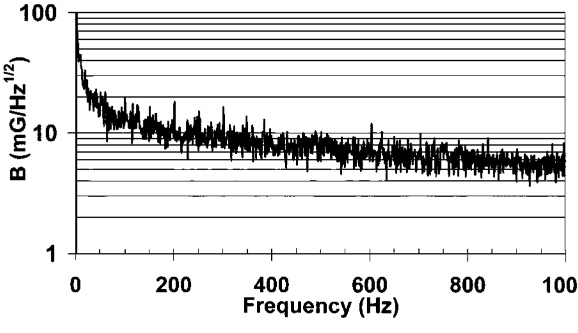
The InSb micro-Hall probes were fabricated using high-quality epitaxial InSb thin films with a thickness of 1 μm grown by MBE on semi-insulating GaAs substrate [9], [10]. Standard room-temperature van der Pauw measurements showed the InSb films to have a carrier concentration of 2 × 10^{12} cm^{-2} and a Hall mobility of 55 500 cm^2/Vs. The process used for the microfabrication of the InSb Hall sensors was similar to the GaAs 2DEG sensors as reported previously [1]. The differences on this occasion were: 1) reactive ion etching was used for Hall probe definition and 2) Ti–Au Ohmic contacts. Fig. 2 shows a typical ~1.5 μm × 1.5 μm InSb micro-Hall probe with a Hall coefficient of $R_H \sim 0.034$ Ω/Gauss and a series resistance of $R_s = 2.2$ kΩ.

III. RESULTS

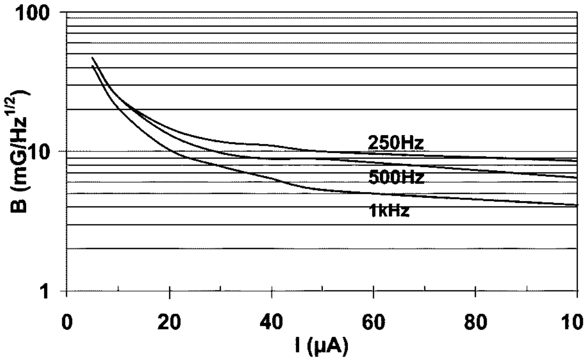
A. Hall Probe Noise Measurements

The InSb micro-Hall sensors were driven with a dc current (I_{HALL}) and the Hall voltage measured using a low-noise amplifier positioned close to the Hall probe. The amplifier's gain and bandwidth were an adjustable parameter. The minimum detectable magnetic field with a Hall probe can be written as [1]

$$B_{\min} = V_{\mathrm{noise}}/(R_H I_{\mathrm{HALL}}) \tag{1}$$



(a)

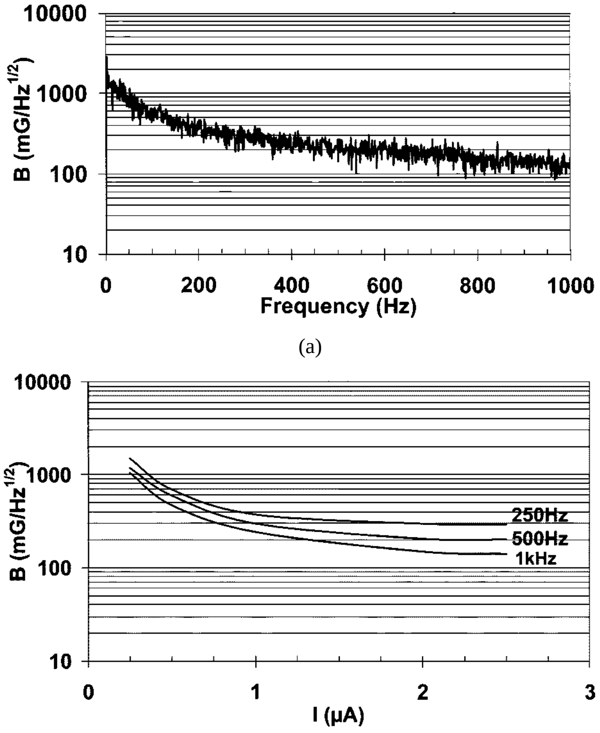


(b)

Fig. 3. (a) Noise spectrum of InSb Hall probe at $I_{\mathrm{HALL}} = 50$ μA. (b) Magnetic field noise of InSb Hall probe as a function of Hall current.

where V_{noise} is the total voltage noise at the input of the Hall amplifier. The V_{noise} has two components; voltage noise of the amplifier and the noise due to the series resistance of the Hall sensor (R_s). It is desirable to drive the Hall probe with the highest permissible current. However, the voltage noise of series resistance R_s increases due to heating of the charge carriers and the lattice. Therefore, the Hall current cannot be increased indefinitely and there is a maximum useable $I_{\mathrm{HALL\,max}}$.

We measured the noise spectra of the InSb micro-Hall sensors at different Hall currents to find optimum operating conditions and $I_{\mathrm{HALL\,max}}$. The gain and bandwidth of the Hall amplifier were set to 10 000 and 1 kHz, respectively. The noise spectra were measured using a fast Fourier transform signal analyzer in a 1 Hz equivalent bandwidth at different Hall currents. Fig. 3(a) shows the noise spectrum for $I_{\mathrm{HALL}} = 50$ μA. Minimum detectable magnetic field is plotted as a function of Hall current in Fig. 3(b) at three different measurement frequencies; 250, 500, and 1000 Hz. The noise decreases slightly at higher frequencies. This could be due to spurious capacitances between the measurement leads of the Hall probe, which reduces the bandwidth of the Hall voltage signal. The minimum detectable magnetic field can be conservatively estimated to be 6–10 mG/$\sqrt{\mathrm{Hz}}$ at $I_{\mathrm{HALL}} = 50$ μA. The new InSb sensors are compared with the Hall probes microfabricated from a GaAs 2DEG material. Fig. 4(a) shows the noise spectrum of the 1.5 μm GaAs Hall sensor with a Hall coefficient of $R_H \sim 0.26$ Ω/Gauss and a series resistance of $R_s = 105$ kΩ at $I_{\mathrm{HALL}} = 2.5$ μA. Minimum detectable magnetic field is plotted as a function of Hall current in Fig. 4(b) at three different measurement frequencies; 250, 500, and 1000 Hz. The noise levels change from sensor to



(a)

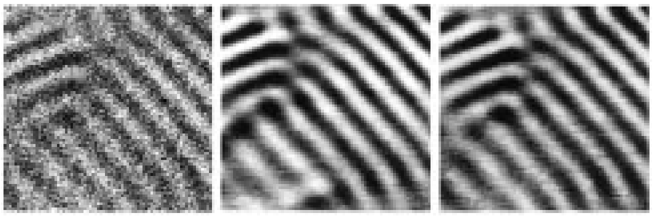
(b)

Fig. 4. (a) Noise spectrum of GaAs 2DEG Hall probe at $I_{\mathrm{HALL}} = 2.5\ \mu\mathrm{A}$. (b) Magnetic field noise of GaAs 2DEG Hall probe as a function of Hall current.

sensor and the data shown in the Fig. 4 is not from the best GaAs 2DEG Hall sensor.

B. Imaging Garnet Crystal With InSb Micro-Hall Probe

The newly developed InSb micro-Hall sensors showed approximately ten times better noise performance compared to conventional GaAs-based sensors used in RT-SHPM. These new InSb thin-film Hall probes were used to image magnetic domain structures of crystalline garnet films which we have studied previously using GaAs 2DEG Hall sensors [11]. The sample is vacuum coated with a thin 20-nm layer of gold film to enable SHPM imaging. Fig. 5(a)–(c) shows 25 μm × 25 μm RT-SHPM images of 5.5-μm-thick crystalline Bi-substituted iron garnet films measured using Hall currents of 3, 30, and 50 μA, respectively. The images are acquired in the liftoff mode with the InSb micro-Hall sensor at a height of 0.35 μm. The black and white regions correspond to surface field fluctuations into and out of the plane of the paper ranging between ±52 G. We did not observe any differences in the images obtained using Hall currents greater than 50 μA.



(a) (b) (c)

Fig. 5. Typical 25 μm × 25 μm RT-SHPM images of 5.5-μm-thick crystalline bismuth-substituted iron garnet films obtained with Hall currents of (a) 3, (b) 30, and (c) 50 μA.

IV. CONCLUSION

InSb micro-Hall probes were shown to be highly promising, low-noise alternatives to GaAs sensors for RT-SHPM with an order of magnitude better performance. Further improvements in the spatial resolution (~50 nm) and magnetic sensitivity of room-temperature InSb Hall probes can be envisaged by using thinner InSb films, InSb quantum wells, and InSb 2DEG structures.

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