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High Sensitivity InSb Ultra-Thin Film Micro-Hall Sensors for Bioscreening Applications

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A high sensitivity, 4.5 μm × 4.5 μm InSb thin film micro-Hall sensor (micro-HS) with a minimum field detection ($B_{\min}$) of 77 nT/(Hz)$^{1/2}$ was developed for bioscreening applications and used for the detection of a single 2.8 μm diameter superparamagnetic microbead by monitoring its ac magnetic susceptibility. The scalability of the InSb micro-HS was demonstrated by fabricating 500 nm × 500 nm InSb nano-Hall sensors with $B_{\min}$ of 0.72 μT/(Hz)$^{1/2}$ that could potentially be used to detect 100 nm sized superparamagnetic particles. [DOI: 10.1143/JJAP.43.L868]

KEYWORDS: biosensor, hall effect, nanoparticles, nanoelectronics, biotechnology, bioscreening, superparamagnetic particles, magnetic labeling, DNA analysis, ac susceptibility

Biological labeling and subsequent detection of polymer microbeads embedded with nanometer sized ferrite particles is increasingly being studied as a low cost, highly selective means of detecting target analytes in bioscreening technology.[1–3] Compared with techniques employing scintillation counting, the use of magnetic labeling offers the advantages of negligible interference from the sample background, long term stability and the possibility of fabricating multianalyte arrays.[4] To-date, a wide range of methods and sensors have been studied for the detection of magnetic microbeads including the use of induction coils,[5] superconducting quantum interference sensors,[6] magnetoresistive sensors (MR)[7–10] and CMOS circuits with integrated silicon Hall sensors.[11,12] A practical biosensor system for detecting microbeads should be rapid, high sensitivity and scalable for the detection of nanometer sized magnetic particles for screening single molecules.[13]

In this paper, in an extension of our research on the applications of high performance micro-Hall sensors,[14–18] we describe the development of high sensitivity InSb micro-Hall sensors (micro-HS) for use in biosensor systems based on the detection of magnetic microbeads. The prototype biosensor instrument was of a simple design, consisting of a coil for generating an ac driving field, a permanent magnetic for applying a dc bias field and a 4.5 μm × 4.5 μm InSb micro-HS for monitoring changes in the magnetic induction of the magnetic microbeads. The minimum field detection ($B_{\min}$) of a Hall sensor can be written as $B_{\min} = V_{\text{noise}}/R_{\text{H}}I_{\text{Hall}}$, where V_{noise}, is the total voltage noise at the input of the Hall amplifier, I_{Hall}, the dc Hall sensor drive current and R_{H}, the Hall coefficient of the material. In our study, the $B_{\min}$ of the InSb micro Hall device was 77 nT/(Hz)$^{1/2}$, at I_{Hall} of 1 mA. The microbead was placed in intimate contact with the active 'cross-region' of the InSb thin film Hall sensor (micro-HS), hence enhancing the detection sensitivity of the system compared with MR and CMOS Si Hall sensors, where design constraints limit the sensor to bead separation to several micrometers.[7,11] Further, the potential scalability and use of the InSb micro-HS for measuring nanometer sized magnetic labels was demonstrated by the fabrication of high sensitivity 500 nm × 500 nm InSb Hall sensors with $B_{\min}$ of 0.72 μT/(Hz)$^{1/2}$.

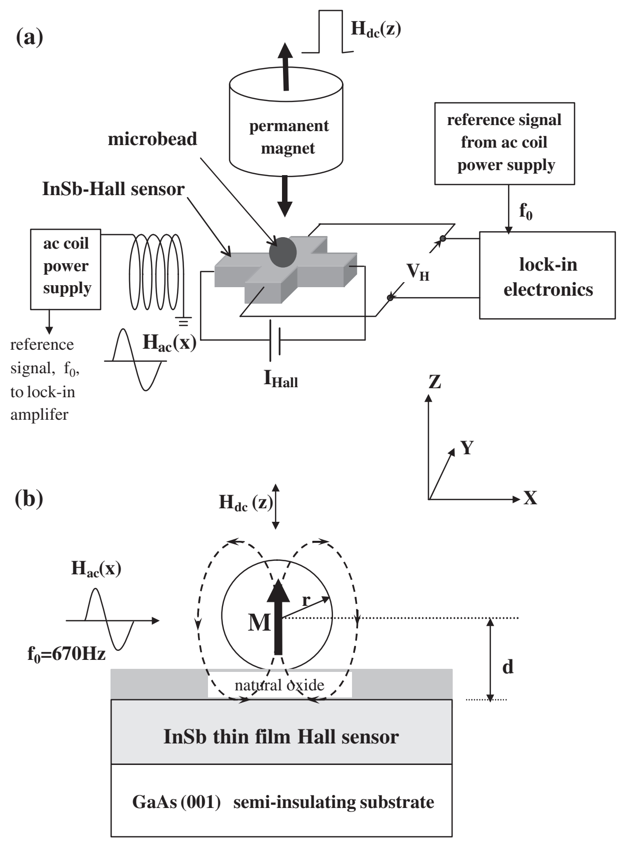

Fig. 1. (a) Schematic illustration of the InSb thin film Hall effect biosensor system and (b) relative positions of the micro-HS and microbead. The bead is detected by applying an ac drive field $H_{\text{ac}}(x)$ [44 Oe at 670 Hz] in the x-direction, and a dc field $H_{\text{dc}}(z)$ [320 Oe] in the z-direction, and using lock-in electronics to monitor the Hall voltage at the same frequency as $H_{\text{ac}}(x)$. A change in the Hall voltage after the application of $H_{\text{dc}}(z)$ indicates the presence of a magnetic microbead.

As schematically shown in Figs. 1(a) and 1(b), the 4.5 μm × 4.5 μm InSb micro-HS is integrated into a system consisting of a compact Helmholtz coil (diameter = 20 mm; 368 turns) for generating an ac field, $H_{\text{ac}}(x)$ and a NbFeB permanent magnetic for applying the bias dc field, $H_{\text{dc}}(z)$. The micro-Hall sensor was fabricated using a 320 nm InSb epilayer (mobility = 17,453 cm^2/V·s; sheet carrier concentration $= 3.6 \times 10^{12}\,\mathrm{cm}^{-2}$) grown on (100) GaAs by molecular beam epitaxy.[19] Conventional photolithography and wet etching was used to define the micro-HS and Ohmic contacts were formed using Ti/AuGe.

Micromanipulators were used to place 2.8 µm diameter magnetic beads (Dynabeads M-270; saturation magnetization of ~16 kA/m at external applied fields of ~20 kA/m[7]) near the center of the active 'cross area' of the InSb micro-HS. The presence of magnetic beads was confirmed by ac susceptibility measurements where a dc field was superimposed on a small ac magnetic field resulting in a time dependent magnetization (magnetic moment) of the microbeads that induced corresponding changes in the Hall voltage of the Hall sensor.[11,20] The detection of changes in the Hall voltage after applying $H_{dc}(z)$ indicates the presence of microbeads.

Figure 2 shows an optical micrograph of a typical 4.5 µm × 4.5 µm micro-HS, in this case with two 2.8 µm microbeads located near its center and others that scattered out of position during micromanipulation. The sensor had a Hall coefficient of 0.037 Ω/G and a series resistance of 1.5 kΩ at room temperature. Fast Fourier spectrum analysis showed the InSb micro-Hall sensor to have B_{min} of 77 nT/(Hz)$^{1/2}$ at an optimal I_{Hall} of 1 mA. Measurements of the frequency dependence of B_{min} showed a small $1/f$ noise component with the minimum field detection being limited by only thermal noise for frequencies above 200 Hz. A detailed account of the electrical properties of the InSb Hall sensors developed in this study will be described elsewhere.

The microbeads were detected using the following experimental procedure: (1) the ac drive field, $H_{ac}(x)$ (44 Oe; 670 Hz) was applied in the same plane as the InSb epilayer; (2) a NbFeB permanent magnet was used to impose the dc bias field, $H_{dc}(z)$ (320 Oe), perpendicular to the plane of the InSb sensor surface; (3) changes in the Hall voltage

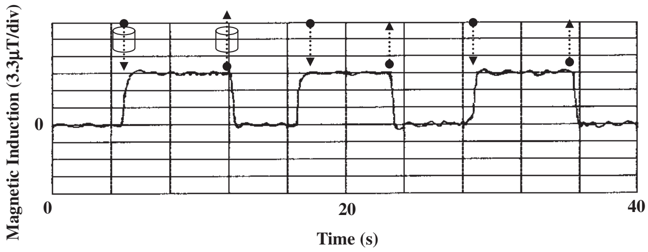

Fig. 3. Real time variation of the magnetic induction on the InSb micro-Hall sensor due to the presence of a single microbead as measured by monitoring changes in Hall voltage after the application (downward arrow) and removal (upward arrow) of the 320 Oe dc field, $H_{dc}(z)$. The ac in-plane field was 44 Oe at 670 Hz and lock-in time constant was 100 ms.

after application of $H_{dc}(z)$ were monitored at the same frequency as $H_{ac}(x)$ using lock-in electronics. This procedure enabled the detection of single microbeads with millisecond response times.

Figure 3 shows the results of a real-time measurement sequence for the detection of a single magnetic bead. The rise time of the Hall voltage after application of $H_{dc}(z)$ was approximately 500 ms with complete synchronization between the application of $H_{dc}(z)$ and changes in the Hall voltage of the InSb micro Hall sensor, indicative of the magnetic induction fluctuations of the microbead.

The feasibility of using the InSb micro-HS for the detection of nanometer sized magnetic particles was studied by fabricating InSb nano-Hall sensors (nano-HS) using Ar ion focused ion beam milling to etch the 4.5 µm × 4.5 µm sized devices to 500 nm × 500 nm dimensions. Figure 4 shows a typical 500 nm × 500 nm nano-HS where the undulations are the surface of a thin layer of photoresist used to protect the InSb thin film during FIB processing. The room temperature series resistance and B_{min} of this device were 6.2 kΩ and 0.72 µT/(Hz)$^{1/2}$ ($I_{Hall} = 100$ µA), respectively.

These InSb nano-HS are promising for the detection of nanometer sized magnetic particles. An important factor in the design of high sensitivity biosensor systems is the bead to sensor separation (d) since the magnetic field from

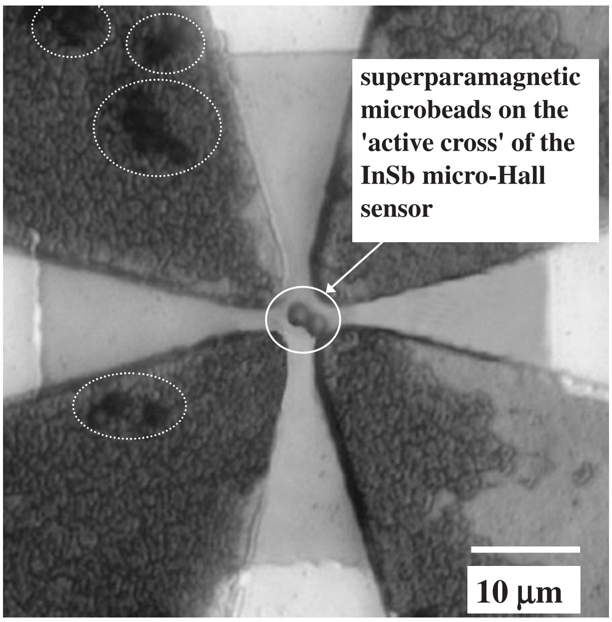

Fig. 2. Optical micrograph of a typical 4.5 µm × 4.5 µm InSb micro-Hall sensor, in this case with two 2.8 µm microbeads located near its center. The regions highlighted by the dotted lines are beads that scattered out of position during micromanipulation.

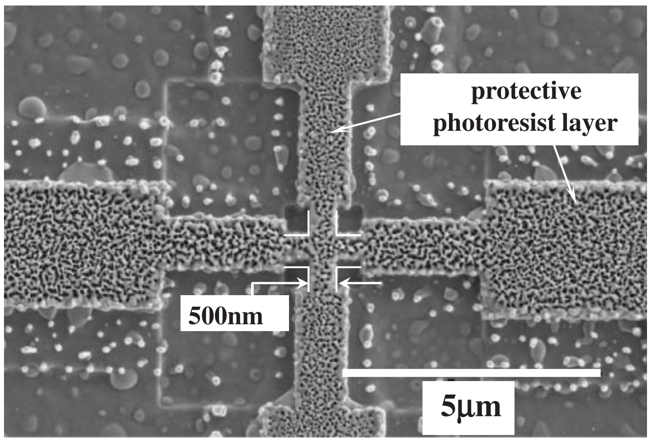

Fig. 4. Electron micrograph of a typical 500 nm × 500 nm InSb nano-Hall device fabricated by focussed ion beam milling. The undulations are the surface of a thin layer of photoresist used to protect the InSb thin film during FIB processing.

Table I. Variation of magnetic field due to a nanoparticle with sensor-to-nanoparticle separation. The single nanoparticle is assumed to have $r = 50\,\mathrm{nm}$, $M_s = 2.4 \times 10^{-2}\,\mathrm{Am^2/g}$ at external field of 1000 Oe, and $r = 1.4 \times 10^6\,\mathrm{g/m^3}$ based on commercially available particles (Micromod, Germany).

Hall sensor to nanoparticle separation (nm)	50	100	200
Magnet field at the sensor due to nanoparticle (G)	280	35	4.4

magnetic beads decreases as $\sim \frac{1}{d^3}$, and this parameter must be minimized in order to optimize the signal to noise ratio of the system. The design of our biosensor instrumentation enabled the positioning of the microbeads in intimate contact with the InSb sensor surface. The following calculation illustrates the superior sensitivity of our InSb Hall sensor based system compared with magnetoresistive and silicon Hall sensors integrated in CMOS circuits.

The magnetic moment, m, of a superparamagnetic particle with a radius r and saturation magnetization M_s, can be determined from the relationship,

$$m = M_s \cdot V \cdot \rho = M_s \cdot \left(\frac{4\pi}{3}\right) r^3 \cdot \rho$$

where, V, is the volume and ρ, the density of the nanoparticle. Further, the magnetic field, B_{dip}, due to a superparamagnetic nanoparticle can be calculated assuming the dipole approximation,[20,21)]

$$B_{dip} = \frac{\mu_o m}{2\pi d^3}$$

where, μ_o, is the permeability of a vacuum and d, the nanoparticle to Hall sensor separation. Table I shows the variation of B_{dip} with d, for a single nanoparticle with $r = 50\,\mathrm{nm}$, $M_s = 2.4 \times 10^{-2}\,\mathrm{Am^2/g}$ at an external field of 1000 Oe, and $\rho = 1.4 \times 10^6\,\mathrm{g/m^3}$ (Micromod, Germany). Comparison of our experimental values of B_{min} for the 500 nm InSb nano-Hall sensors ($B_{min} = 0.72\,\mu\mathrm{T/(Hz)^{1/2}}$) and the results of these calculations shows that B_{min} of the InSb nano-Hall sensors would facilitate the detection of a single 100 nm diameter nanoparticles even at a sensor to particle separation of 200 nm, where $B_{dip} = 440\,\mu\mathrm{T}$.

In summary, a prototype biosensor system incorporating a scalable, high sensitivity $4.5\,\mu\mathrm{m} \times 4.5\,\mu\mathrm{m}$ InSb thin film micro-HS was developed and used for the detection of single $2.8\,\mu\mathrm{m}$ diameter superparamagnetic beads. Focused ion beam lithography was used to fabricate a $500\,\mathrm{nm} \times 500\,\mathrm{nm}$ InSb nano-HS potentially capable of detecting 100 nm diameter superparamagnetic nanoparticles at a sensor to nanoparticle separation of 200 nm. We have initiated a series of experiments to fabricate arrays of InSb nano-Hall sensors for bioscreening applications.

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1) *Scientific and Clinical Applications of Magnetic Carriers*, eds. U. Hafeli, W. Schutt, J. Teller and M. Zborowski (Pelnum, New York, 1997).
2) Q. A. Pankhurst, J. Connolly, S. K. Jones and J. Dobson: J. Phys. D **36** (2003) R167.
3) S. Hatanaka, N. Matsushita and M. Abe, K. Nishimura, M. Hasegawa and H. Handa: J. Appl. Phys. **93** (2003) 7569.
4) M. M. Miller, P. E. Sheehan, R. L. Edelstein, C. R. Tamanaha, L. Zhong, S. Bounnak, L. J. Whitman and R. J. Colton: J. Mag. Magn. Mat. **25** (2001) 138.
5) C. B. Kriz, K. Radevik and D. Kriz: Anal. Chem. **68** (1996) 1966.
6) R. Kotitz, H. Matz, L. Trahms, H. Koch, W. Weitschies, T. Rheinlander, W. Semmler and T. Bunte: IEEE Trans. App. Superconduct. **7** (1997) 3678.
7) D. R. Baselt, G. U. Lee, M. Natesan, S. W. Metzger, P. E. Sheehan and R. J. Colton: Biosensors & Bioelectronics **13** (1998) 731.
8) R. L. Edelstein, C. R. Tamanaha, P. E. Sheehan, M. M. Miller, D. R. Baselt, L. J. Whitman and R. J. Colton: Biosensors & Bioelectronics **14** (2000) 805.
9) D. L. Graham, H. A. Ferreira, J. Bernardo, P. P. Freitas and J. M. S. Cabral: J. Appl. Phys. **91** (2002) 7786.
10) M. Tondra, M. Porter and R. J. Lipert: J. Vac. Sci. & Technol. A **18** (2000) 1125.
11) P. A. Besse, G. Boero, M. Demierre, V. Pott and R. Popovic: Appl. Phys. Lett. **80** (2002) 4199.
12) T. Aytur, P. R. Beatty, B. Boser, M. Anwar and T. Ishikawa: Solid-State Sensor, Actuator & Microsystems Workshop (2002) 126.
13) D. L. Graham, H. A. Ferreira, P. P. Freitas and J. M. S. Cabral: Biosens. Bioelectron. **18** (2003) 483.
14) A. Sandhu, H. Masuda, A. Oral and S. J. Bending: Jpn. J. Appl. Phys. **40** (2001) 4321.
15) A. Sandhu, H. Masuda, K. Kurosawa, A. Oral and S. J. Bending: Electron. Lett. **37** (201) 1335.
16) A. Sandhu, N. Iida, H. Masuda, A. Oral and S. J. Bending: J. Magn. & Magnetic Mater. **242** (2002) 1249.
17) A. Sandhu, H. Masuda, A. Oral and S. J. Bending: Ultramicroscopy **91** (2002) 97.
18) A. Sandhu, H. Masuda and A. Oral: IEEE Trans. Magnetism **39** (2003) 123.
19) I. Shibasaki, A. Okamoto, A. Ashihara and K. Suzuki: Tech. Dig. 18th Sensor Symp. (2001) 233.
20) B. Yellen, G. Friedman and A Feinerman: J. Appl. Phys. **91** (2002) 8552.
21) R. Lawrence Comstock: *Introduction to Magnetism and Magnetic Recording* (John Wiley & Sons, Inc, 1999).