Multi-Functional Hall Effect Probes for Magnetic Imaging and Biosensing

Adarsh SANDHU
Quantum Nanoelectronics Research Center (QNERC), Tokyo Institute of Technology,
2-12-1 O-okayama, Meguro-ku, Tokyo, 152-8552
sandhu.a.aa@m.titech.ac.jp

Novel applications of micro and nano-Hall effect sensors are described. A unique scanning Hall probe microscopy system developed and used for the quantitative and non-invasive imaging of localized magnetic fields at the surfaces of magnetic materials under external fields upto 3T. Functionalized Hall biosensor arrays enabled detection of DNA molecules labeled with superparamagnetic particles. .

Edwin Hall's observation that a magnetic field distorts the equipotential lines in a current-carrying conductor, the Hall effect, is the basis of a multimillion dollar industry. Hall effect sensors are ubiquitous devices used in vending machines, modern electronics equipment for controlling DC motors in VCRs, CD-ROM drives and more recently even for reducing the power consumed by electric motors in household washing machines [1, 2].

We have developed a scanning Hall probe microscope system (SHPM) for magnetic imaging ferromagnetic domains [3]. The Hall probes are fabricated using GaAs/AlGaAs 2-DEG heterostructures, InSb thin films, GaAs/InGaAs pseudomorphic heterostructures and bismuth thin films. They exhibit minimum field sensitivities ranging between 6 mG/ $(Hz)^{1/2}$ to 0.8G/ $(Hz)^{1/2}$. Bismuth films are used for fabricating 50nm x50nm Hall sensors for high spatial resolution imaging. Fig. 1 shows quasi-real time SHPM images of bismuth-substituted ferrite garnets (BSG) under external magnetic bias fields. The initial 'magnetic bubbles' evolve into striped domains after one cycle. It is not possible to obtain such information using VSM measurements.

In order to circumvent the limited movement of piezoelectric tubes at cryogenic temperatures, we developed a variable temperature SHPM system (VT-SHPM) capable of scanning areas of hundreds of micrometers with nanometer scale spatial resolution [4]. Fig.2 shows VT-SHPM images of the temperature dependence of magnetic domain size in BSG thin films. The average domain size increases with decreasing measurement temperature. The VT-SHPM will find further applications for testing the integrity of microelectronic circuits, IC cards, and MRAM structures by monitoring magnetic fields induced by currents in such devices.

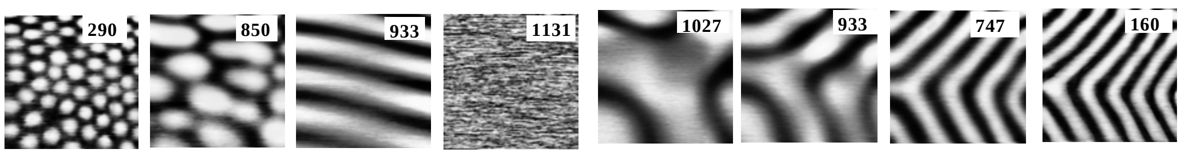

Fig. 1: Typical 25 μm x 25μm SHPM images obtained at 300K of a 5.5 μm BSG film under external perpendicular bias fields (Oe) as indicated. The initial 'bubble domains' are seen to transform into striped features. The black and white regions represent domains with magnetizations into and out of the plane of the paper where the measured fields range between ±118G.

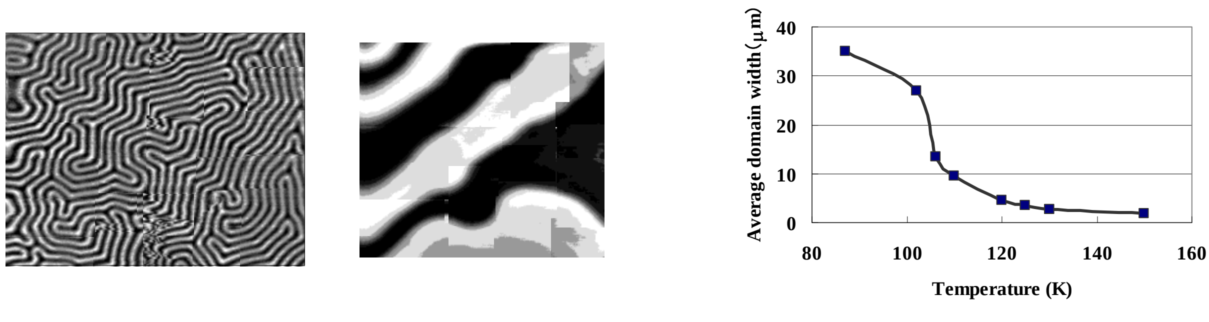

Fig.2: VT-SHPM images of a 5.5 μm single BSG film measured at (LEFT) 300K (120μm x 130μm) and (RIGHT) 77K (110μm x 115μm). The graph shows the temperature dependence of the average domain size of a 5.5 μm BSG film.

We are also developing instrumentation incorporating micro-Hall sensors for medical diagnosis and bioscreening based on biological labeling and electrical detection of superparamagnetic particles [5, 6]. Such technology shows great potential as a low cost, highly selective means of detecting target analytes in human fluids as well as a tool for basic research on molecular recognition processes (Figs. 3-6).

In a typical biosensor system incorporating magnetic beads, the target molecules are attached to a magnetic bead ('label') and passed over a magnetic field sensor with a biologically functionalized surface prepared in such as way as to 'trap' the specific target of interest. A change in the electrical resistance of the sensor indicates the presence of a magnetic bead in extremely close proximity to the sensor surface. 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. The basic requirements of a magnetic bead detection system are: (i) High magnetic sensitivity by minimization of particle-sensor separation: The magnetic field, B_{dip}, due to a superparamagnetic particle can be calculated assuming the dipole approximation, $B_{dip}=[\mu_0 m/2\pi d^3]$, where, m is the magnetic moment, μ_0, permeability of free space, and d, the particle-sensor separation. For a single nanoparticle with a radius of 50nm, (M_s=2.4x10^{-2} Am^2/g, ρ = 1.4x10^6 g/m^3) then the B_{dip}~4.4x10^{-4} T at a sensor-particle separation of 200nm; (ii) Accuracy and high throughput: Rapid completion of the detection and removal cycle; (iii) Scalability: Fabrication of sub-micron sensors for detection of single magnetic beads and molecules; (iv) Sensor surface should permit functionalization; (v) CMOS and/or GaAs compatibility; circuitry; (vi) Low cost. We have demonstrated the use of 2-DEG heterostructures (GaAs/InGaAs) and high electron mobility InSb/InAs thin film micro-Hall sensors for the detection of single magnetic beads [5]. Hall effect sensors are particularly suited for such applications because they offer scalability whilst maintaining sensitivity and have the added advantage of well established processing technology for fabricating sensor arrays integrated with conventional circuits for signal processing. Ultra-high sensitive Hall biosensor arrays were used for the rapid detection of DNA with a sensitivity of ~1000 times greater than conventional fluorescence DNA chip platforms [6].

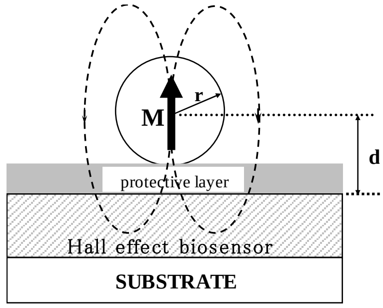

Fig.3. Illustration of the relative positions of the Hall biosensor and magnetic bead used for labeling biomolecules.

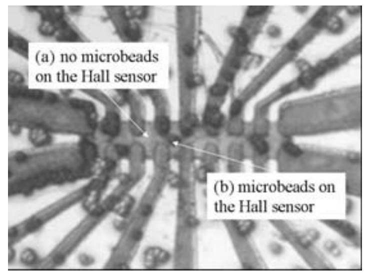

Fig. 4. Optical micrograph of 2.8μm diameter magnetic beads on a 5 μm ×5 μm Hall biosensor array.

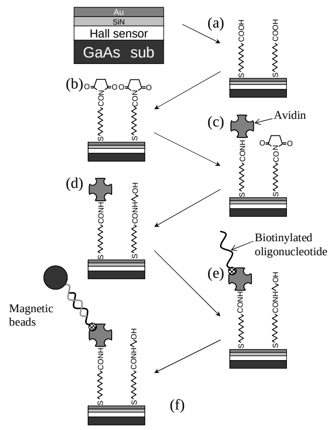

Fig.5. A method used for Immobilizing functionalized magnetic beads utilizing hybridization between complementary oligonucleotides.

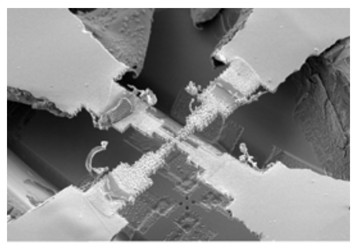
Fig.6. InAs/InSb nano-Hall biosensor bridge (50nmx50nm) fabricated by selective etching and focused ion beam lithography.

REFERENCES
1. E.H. Hall, American Journal of Mathematics 2, 287-292, (1879).
2. Gen Kida, *Development and Future Prospects of High Sensitivity InSb/InAs Thin Film Hall Sensors,* III-Vs Review, 16, p. 24, 2003.
3. A. Sandhu, I. Shibasaki and A. Oral, *Nano and Micro Hall-effect Sensors for SHPM,* Microelectronic Engineering, 73-74, p.524, 2004.
4. A. Sandhu, H. Masuda, H. Senoguchi and K. Togawa, *Novel Variable Temperature Scanning Nano-Hall Probe Microscope System for Large Area Magnetic Imaging Incorporating Piezoelectric Actuators Maintained at Room Temperature*, Nanotechnology, 15, p.410, 2004.
5. A. Sandhu, H.Sanbonsugi, M.Abe, H.Handa, *High Sensitivity InSb Ultra-Sensitive Thin Film Micro-Hall Sensors for Bioscreening Applications,* Jpn. J. Appl. Phys. 43, L868-L870, 2004.
6. A. Sandhu, Y. Kumagai, S. Sakamoto , M. Abe, H. Handa, Biose nsors and Bioelectronics, Biosensors and Bioelectronics 22, p.2115, (2007).