

Scanning Hall Probe Microscopy (SHPM) Using Quartz Crystal AFM Feedback

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Scanning Hall Probe Microscopy (SHPM) is a quantitative and non-invasive technique for imaging localized surface magnetic field fluctuations such as ferromagnetic domains with high spatial and magnetic field resolution of ~ 50 nm and 7 mG/Hz^{1/2} at room temperature. In the SHPM technique, scanning tunneling microscope (STM) or atomic force microscope (AFM) feedback is used to keep the Hall sensor in close proximity of the sample surface. However, STM tracking SHPM requires conductive samples; therefore the insulating substrates have to be coated with a thin layer of gold. This constraint can be eliminated with the AFM feedback using sophisticated Hall probes that are integrated with AFM cantilevers. However it is very difficult to micro fabricate these sensors. In this work, we have eliminated the difficulty in the cantilever-Hall probe integration process, just by gluing a Hall Probe chip to a quartz crystal tuning fork force sensor. The Hall sensor chip is simply glued at the end of a 32.768 kHz or 100 kHz Quartz crystal, which is used as force sensor. An LT-SHPM system is used to scan the samples. The sensor assembly is dithered at the resonance frequency using a digital Phase Locked Loop circuit and frequency shifts are used for AFM tracking. SHPM electronics is modified to detect AFM topography and the frequency shift, along with the magnetic field image. Magnetic domains and topography of an Iron Garnet thin film crystal, NdFeB demagnetised magnet and hard disk samples are presented at room temperature. The performance is found to be comparable with the SHPM using STM feedback.

Keywords: Scanning Hall Probe Microscopy, Quartz Crystal, AFM.

1. INTRODUCTION

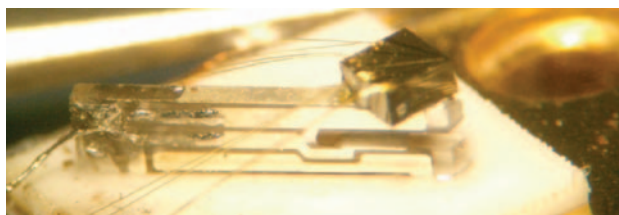
Scanning Hall Probe Microscopy (SHPM)¹ is a quantitative and non-invasive technique for imaging localized surface magnetic field fluctuations such as ferromagnetic domains with high spatial and magnetic field resolution of ~ 50 nm² and 7 mG/Hz at room temperature. This new technique offers advantages and complements the other magnetic imaging methods like magnetic force microscopy (MFM),³ Magnetic Near Field Scanning Optical Microscopy⁴ and Kerr Microscopy.⁵ In the SHPM technique, scanning tunneling microscope (STM)¹ or atomic force microscope (AFM)^{6,7} feedback is used to keep the Hall sensor in close proximity of the sample. However, STM tracking SHPM requires conductive samples; therefore the insulating substrates have to be coated with a thin layer of gold. Moreover, the tip used in STM tracking

SHPM is typically 50 nm gold film that can wear off easily and damage to the Hall sensor follows very quickly. These constraints can be eliminated with the AFM feedback using sophisticated Hall probes that are integrated with piezoresistive⁷ and SiN AFM cantilevers.⁸ However it is relatively difficult to micro fabricate these sensors. Quartz crystal force sensors⁹ have been used in SPM for a wide range of applications as the force sensing is performed using a single current to voltage converter. They have also been used to track the sample surfaces in Scanning Squid Microscopy¹⁰ where the SQUID chip is glued directly on the quartz tuning fork. In this work, we have eliminated the difficulty in the cantilever-Hall probe integration process and simplified the process just by gluing a Hall Probe chip at the end of a quartz crystal tuning fork force sensor. The resultant SHPM is simple to run as it uses self sensing quartz force sensors and can operate reliably at room temperature with a better lifetime performance than STM tracking.

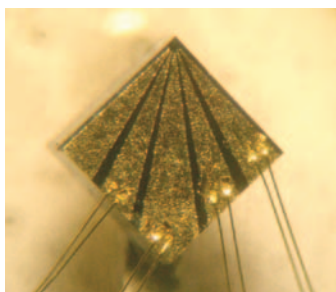
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2. EXPERIMENTAL DETAILS

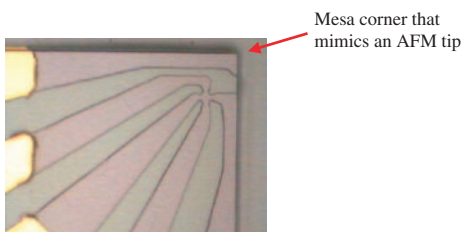
The $1\ \mu\text{m}$ size Hall sensors are microfabricated in a Class 100 clean room facility using optical lithography. The semiconductor wafer used is MBE grown P-HEMT and AlGaAs/GaAs 2DEG materials. The carrier concentration of the samples were $2.1 \times 10^{13}\ \text{cm}^{-2}$ for P-HEMT and $3.6 \times 10^{11}\ \text{cm}^{-2}$ for 2DEG. The mobility of both samples was around $6000\ \text{cm}^2/\text{Vs}$ at 300 K. Four hall sensors are microfabricated on a chip and they are diced to a size of $2.5 \times 2.5 \times 0.5$ and $1 \times 1 \times 0.5$ mm. Details of the process is described elsewhere.¹ The quartz crystals are extracted from their can while squeezing with a pair of pliers and detached from the electrical leads using a heat gun. Afterwards, they are fixed on a printed circuit board sensor holder with one prong fixed using epoxy and electrical contacts to the electrodes on the quartz fork are soldered. The Hall sensor chip is then attached using a low temperature compatible glue at the end of 32.768 kHz and 100 kHz quartz crystals, which are used as force sensor as shown in Figure 1. The wiring to the Hall sensor is established using $12\ \mu\text{m}$ gold bond wires with a wire bonder. Figure 2 shows a typical $\sim 1\ \mu\text{m} \times 1\ \mu\text{m}$ micro-Hall probe with a Hall coefficient of $R_H \sim 0.175\ \Omega/\text{Gauss}$ and



(a)



(b)



(c)

Fig. 1. A micro fabricated $1 \times 1 \times 0.5$ mm Hall probe mounted on a 100 kHz quartz crystal fork. (a) Side view, (b) top view, and (c) sensor detail.

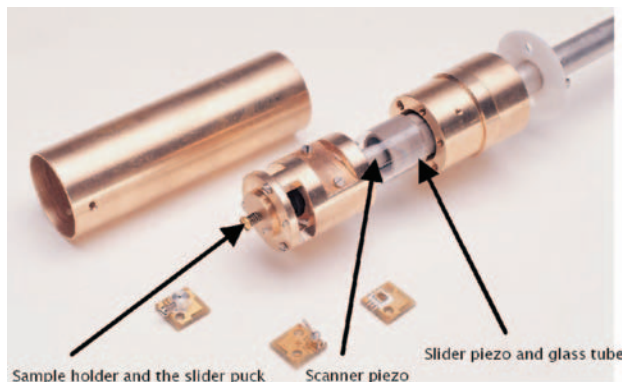


Fig. 2. LT-SHPM Head used in the experiments.

a series resistance of $R_s = 55\ \text{k}\Omega$ at 300 K or 2DEG Hall sensor. The dimensions ($l \times w \times t$) of the quartz crystal's prongs are, $3.81 \times 0.34 \times 0.62$ mm for 32.768 kHz and $1.72 \times 0.32 \times 0.4$ mm for 100 kHz tuning forks, resulting in stiffness of 29 kN/m and 200 kN/m, respectively. Initially 32.768 kHz quartz crystals and sensor chip sizes of $2.5 \times 2.5 \times 0.5$ mm (~ 17 mg) were used. This combination gives a typical resonance frequency of ~ 5 – 6 kHz for the sensor. Even though these low frequency sensors have worked reasonably well, we wanted to increase the resonance frequency of the sensor for faster scan rates. Therefore, we reduced the chip size to $1 \times 1 \times 0.5$ mm (~ 2.7 mg) and employed smaller and stiffer 100 kHz tuning forks, which produced a much higher, ~ 29 – 33 kHz resonance frequency. A commercial LT-SHPM system¹¹ is used to perform the experiments as shown in Figure 2. The sensor assembly is dithered at the resonance frequency with the split section on the scan piezo using a digital Phase Locked Loop and frequency shifts are used for AFM tracking. SHPM electronics is modified to detect AFM topography and the phase, along with the magnetic field image. The Hall sensor is positioned $12\ \mu\text{m}$ away from the corner of a deep etch mesa, which serves as AFM tip. The sample is tilted $\sim 1.25^\circ$ with respect to Hall probe chip ensuring that the corner of the mesa is the highest point. The microscope can be operated in two modes: AFM tracking and lift-off mode. Even though a relatively heavy mass is attached at the end of tuning fork, we usually get a quality factor (Q) of more than 200. The system is usually operated in a pressure of 1×10^{-4} mbar. However, we can also reliably operate the system in atmospheric pressures. Despite a more or less planar geometry, the viscous damping is not a big problem due to high stiffness of the sensor.

3. RESULTS

We have imaged magnetic domains and topography of the Iron Garnet thin film crystal and NdFeB demagnetised magnet to show the performance of the microscope.

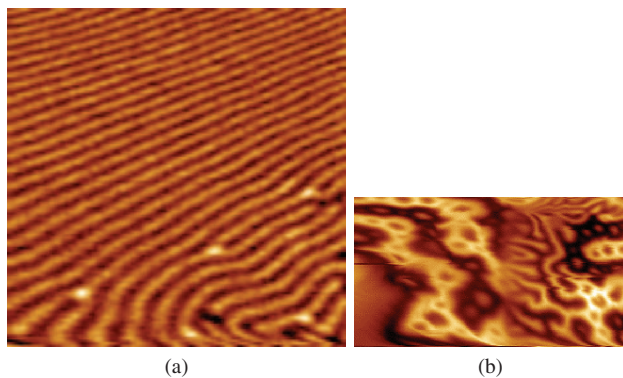


Fig. 3. SHPM image of (a) iron garnet crystal and (b) NdFeB demagnetised magnet obtained in AFM Tracking mode. Size of the images and vertical scale of the images are (a) $40 \times 40 \mu\text{m}$ and 38 Gauss, and (b) $54 \times 20 \mu\text{m}$ and 3,330 Gauss, respectively.

A sensor with 32.768 kHz tuning fork and a $2.5 \times 2.5 \times 0.5 \text{ mm}$ size P-HEMT Hall sensor chip is used, giving a resonance frequency of 5.297 kHz. The Hall coefficient of the sensor was $R_H \sim 0.003 \Omega/\text{Gauss}$ and a series resistance of $R_s \sim 3 \text{ k}\Omega$ at 300 K. The oscillation amplitude was $\sim 50 \text{ nm}$ with a $Q \sim 230$. The AFM feedback is established with 15 Hz positive frequency shift. The scan speed was $2 \mu\text{m/s}$. Figure 3 shows AFM Tracking SHPM images of Iron garnet (a) and NdFeB demagnetised magnet (b) samples obtained at 300 K. The Hall sensor current was $300 \mu\text{A}$ and a low noise DC amplifier is used to detect Hall voltage.

We have also imaged a hard disk sample at 300 K with the Quartz Crystal AFM feedback using 100 kHz tuning fork combined with a smaller $1 \times 1 \times 0.5 \text{ mm}$ size 2DEG Hall sensor chip. The resultant resonance frequency of the combined sensor was 35.620 kHz. The Hall coefficient of the sensor was $R_H \sim 0.175 \Omega/\text{Gauss}$ and a series resistance of $R_s = 55 \text{ k}\Omega$ at 300 K. The oscillation amplitude was $\sim 50 \text{ nm}$ with a $Q \sim 200$. The AFM feedback is established with 5 Hz positive frequency shift. The scan speed was $2 \mu\text{m/s}$. The Hall sensor was driven with a $3 \mu\text{A}$ DC Hall current and a low noise DC amplifier is used to detect Hall voltage. Figure 4 shows simultaneously obtained SHPM and AFM images of the sample.

4. DISCUSSIONS AND CONCLUSIONS

Combination of Hall probes and quartz crystal force sensors result in a cheap and easy fabrication of AFM tracking SHPM sensors. Reliable operation and long lifetimes have been achieved compared to STM tracking SHPM. Even though the mesa corner was not supposed to be a sharp edge, we get reasonable resolution in AFM images. In conclusion, the performance is found to be comparable with the SHPM using STM feedback. This method eliminates the necessity of conducting samples for SHPM and

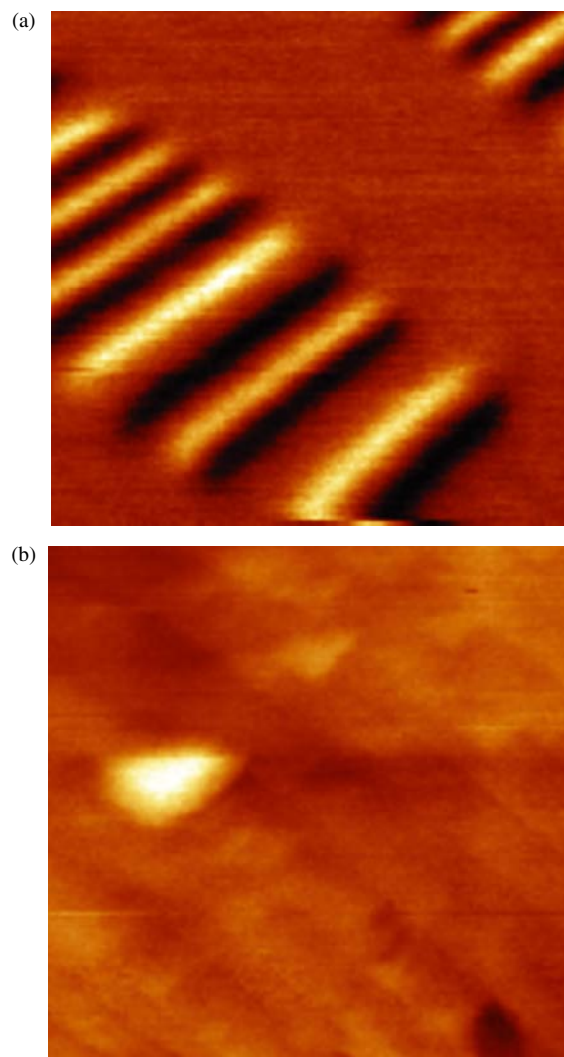


Fig. 4. SHPM image of (a) Hard disk specimen and (b) simultaneously obtained topography. Size of the images are $50 \times 50 \mu\text{m}$ and vertical scales are (a) 256.9 Gauss and (b) 91 nm.

will be very useful for inspection of magnetic devices like MRAM and Hard disk plates, during the manufacturing process I. In SHPM the lateral resolution is determined by the sensor size as well as sensor-sample separation. Since there is no need to fabricate an STM tip, it is possible to bring the Hall sensor closer to the mesa corner. Therefore AFM tracking SHPM using quartz crystal tuning forks helps bringing the sensor closer to the sample for high resolution SHPM, $< 50 \text{ nm}$.

Acknowledgments: This work is supported in Turkey by TÜBİTAK, Project Numbers: TBAG-(105T473), TBAG-(105T224), TBAG-(105T035) and by EU through FP6 NANOMAN Project. We are grateful for Muharrem Demir for his continuous support for the upkeep of the microscope. AO thanks Turkish Academy of Sciences (TÜBA) for financial support.

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Received: 23 June 2006. Revised/Accepted: 15 February 2007.