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Direct and Real-Time Observation of Sub-Micron Domain Dynamics in Magnetically Biased Strontium Ferrite Permanent Magnets by Room Temperature Scanning Micro-Hall Probe Microscopy

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ABSTRACT

A room temperature scanning micro-Hall probe microscope (RT-SHPM) was used for imaging stray magnetic field fluctuations at the surfaces of strontium ferrite permanent magnets (SFM) in the presence of external bias fields. The RT-SHPM enables the extremely fast, non-invasive, and quantitative measurement of localized surface magnetic fields on the sub-micron-scale. A 0.8 x 0.8 μm^2 GaAs/AlGaAs micro-Hall probe (300K Hall coefficient =0.3Ω/G; field sensitivity=0.04 G/√Hz) with an integrated STM tip for precise vertical positioning was used as a magnetic field sensor. External bias fields (H_{ex}) of up to 2700 Oe were applied parallel to the easy and hard axes of thermally demagnetized SFMs. Sample areas of up to 50x50 μm were imaged at a height of 0.3 μm above the SFM surface for each H_{ex}, with scan speeds of approximately one frame/second (128x128 pixels) enabling quasi-real time imaging in synchronization with bias field changes. RT-SHPM images of surfaces normal to the easy axis of demagnetized samples at H_{ex}=0, clearly showed the presence of 8-15 μm sized domains and stray magnetic field fluctuations of ±200G; images of surfaces normal to the hard axis showed 20 μm sized domains with magnetic field fluctuations of ±100G. Pronounced domain movement and rotation was observed for surfaces normal to the easy axis at bias fields above 700 Oe applied along the easy axis. A good correlation was found between domain movement and vibrating sample magnetometer hysteresis measurements. The RT-SHPM system was demonstrated to be a valuable tool for the direct and non-invasive study of micro-magnetic phenomena in ferromagnetic materials.

INTRODUCTION

The development of ferromagnetic materials for high performance permanent magnets requires a fundamental understanding of the behavior magnetic domains in external bias fields.

To-date, magnetic force microscopy (MFM) has been extensively used for imaging magnetic domains of a wide range of materials [1]. However, it has been found that the interpretation of MFM images can be complicated due to artifacts arising from the MFM tip field [2]. The situation is even more complex when the MFM imaging is carried out in the presence of external bias fields [3].

In this paper we describe the unique features of a new versatile room temperature scanning Hall probe microscope (RT-SHPM) system used for the direct, non-invasive, and quantitative imaging of domains at the surface of strontium ferrite permanent magnets in the presence of large external magnetic fields.

EXPERIMENTAL

Figure 1 is a schematic diagram of the RT-SHPM system used in this study [4]. It consists of a GaAs/AlGaAs micro-Hall probe (HP) mounted onto a piezoelectric scanning tube (PZT) at a tilt angle of 1.5° with respect to the sample surface. A scanning tunnelling microscope (STM) tip is integrated adjacent to the HP for precise vertical positioning. The coil is used for calibrating the

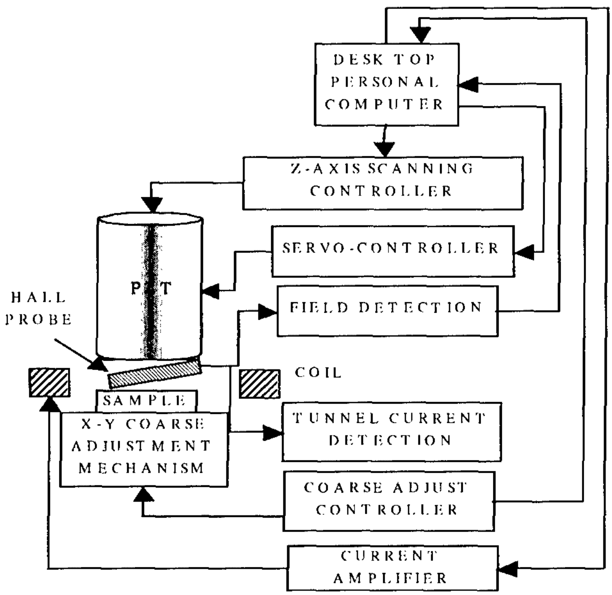


Figure 1. Schematic of the main components of the Room Temperature Scanning Hall Probe System

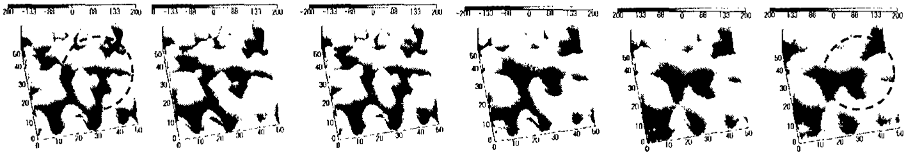
Hall probe. Magnetic imaging was carried out by scanning the HP over the surface of the sample while simultaneously measuring changes in Hall voltage that are proportional to fluctuations of the perpendicular component of the stray magnetic field emanating from the surface. All measurements were made at a height of 0.3μm above the sample surface.

The unique features of the RT-SHPM include: (i) the tilt angle between the HP and sample surface is precisely adjusted using an electronic angle sensor coupled to the PC control software; (ii) coarse sample approach is achieved by a high resolution motorized z-stage with a 25 mm range; (iii) scan range up to 50x50 μm^2; (iv) the use of electrodes on the reverse-side of the Hall probe chip carrier for electrical connection of the Hall bar and STM tip to the control and biasing electronics; (v) data acquisition with a choice of 3 modes including the *STM/SHPM mode* where scanning is carried out while simultaneously monitoring STM tip tunnel current thus enabling topographic imaging and the *real time mode*, where a 128 x 128 pixel scan is possible in about 1 second. The HP was fabricated by photolithography using a GaAs/AlGaAs heterostructure grown by MBE with a two dimensional electron gas density of 2 x 10^{11} cm^{-2} and mobility of 400,000 cm^2/Vs, at 4.2K. The Hall probe was located 13 micrometers away from the chip corner that was coated with a thin gold layer to act as the STM tip. The Hall probe had an active area of ~ 0.8 x 0.8 μm^2, a room temperature Hall coefficient of the HP was 0.3Ω/G and a field sensitivity of 0.04 G/√Hz. The STM tip was not coupled to the Hall bar thus reducing noise during measurement. A Hall drive current of 3 μA was used for all the measurements. A unique set of program routines were developed for the static and animated 3D visualization of SHPM data using Interactive Data Language [5].

The samples studied were cut from a strontium ferrite permanent magnet (SFM) and surfaces normal to the easy and hard axes polished until the undulations were less than 0.2 μm as measured by the STM tip integrated with the HP. Typical dimensions of the resulting samples were 5x5mm with a thickness of 400 μm. The external stepped bias fields (H_{ex}) were applied using a neodymium iron boride permanent magnet incorporated into the RT-SHPM system enabling bias fields of up to 2700 Oe to be applied perpendicular to the polished surfaces. The use of a permanent magnet for applying external bias fields eliminates sample heating problems associated with electromagnets. The external fields were applied in regular steps and the RT-SHPM scan carried out in synchronization at one frame/second (128x128 pixels). The SF samples were also characterized using a vibrating sample magnetometer (VSM) to compare the RT-SHPM results with conventional macroscopic measurements methods.

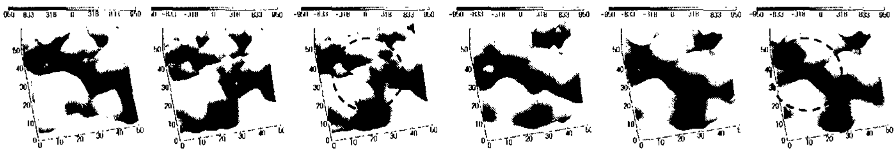
RESULTS AND DISCUSSION

There was no observable correlation between the STM topography and magnetic images for any of the samples studied. Figure 2 shows representative 50x 50 μm scans (surface normal to the easy axis) of the variation of surface magnetic field fluctuations with increasing H_{ex} along the



300 850 1250 1850 2250 2700

Figure 2. External bias field (Oe) dependence of RT-SHPM images (50x50µm) for SFM initially in the demagnetized state. Image surface is normal to the easy axis



-300 -850 -1250 -1850 -2250

Figure 3. External bias field (Oe) dependence of RT-SHPM images (50x50µm) for SFM initially in the remanent state. Image surface is normal to the easy axis.

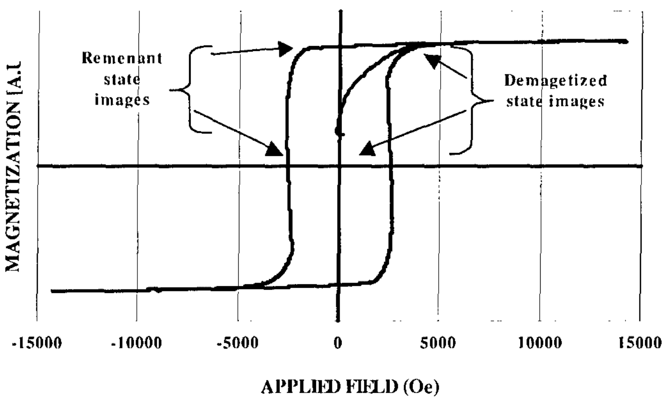
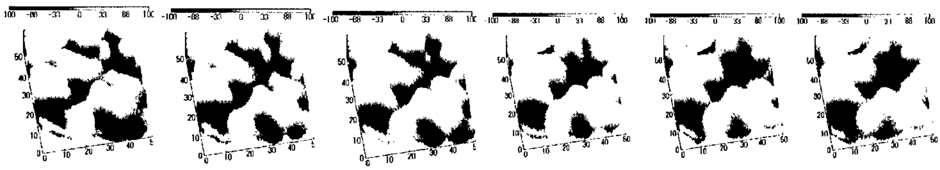


Figure 4. VSM magnetization curve along the easy axis of the SFM

easy axis of a SFM initially in a demagnetized state. Figure 3 shows the images for a sample initially at the remanent state as H_{ex} was increased to –2700 Oe along the easy axis. The black and white regions in the RT-SHPM images represent domains with magnetizations into and out



300 **850** **1250** **1850** **2250** **2700**

Figure 5. External bias field (Oe) dependence of RT-SHPM images (50x50μm) for SFM initially in the demagnetized state.. Image surface is normal to the hard axis.

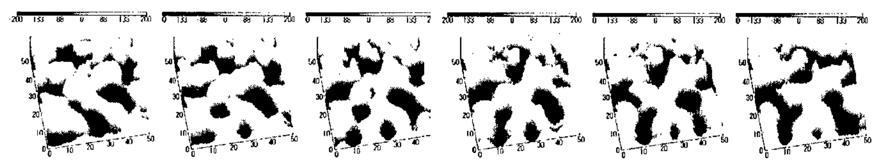


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Figure 6. External bias field (Oe) dependence of RT-SHPM images (50x50μm) for SFM initially in the remanent state. Image surface is normal to the hard axis.

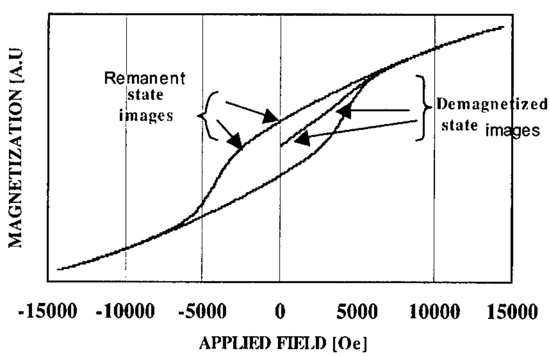

Figure 7. VSM magnetization curve along the hard axis of the SFM

of the plane of the paper. The corresponding VSM hysteresis loop is shown in figure 4. Figures 5 and 6 show the H_{ex} dependence of RT-SHPM images of surfaces normal to the hard axis starting at the demagnetized and remanent states, respectively. Figure 7 is the VSM loop along the hard axis.

The RT-SHPM images show magnetic regions on the sample with magnetization perpendicular to its surface due to the existence of clusters of multi-domain grains. The SFM samples used in this study were produced by a process involving sintering and had grain sizes ranging between 2-10 micrometers [6,7]. A comparison of the RT-SHPM images in figures 2 and 5 at H_{ex} = 300 Oe shows the domains of samples along the easy axis to be smaller (5~10 μm) than those along the hard axis (~20 μm). These differences can be attributed to differences in the size of grains along these two orthogonal directions as has also been observed in other materials used for fabricating permanent magnets [8]. The RT-SHPM images also reveal the size of domains to vary with H_{ex}. An example of domain movement followed by rotation can be seen in the regions marked by broken circles in figures 2 and 3. The changes in the gray scale contrast indicate changes in direction of the magnetization of the domains due to the external bias. The movement and rotation of the domains was particularly pronounced in the case of SFM surfaces normal to the easy axis. These microscopic observations correlate with VSM measurements, where a rapid change in magnetization is observed along the easy direction (figure 4) but the contrary when H_{ex} was applied along the hard axis (figure 7). The surface stray magnetic fields measured by the RT-SHPM (shown by the gray scale above the images) were greater along the easy axis than the hard axis in both the demagnetized and remanent states. A detailed micro-magnetic evaluation of these results is in progress and the results will be reported elsewhere.

CONCLUSION

The RT-SHPM system was demonstrated to be a valuable tool for the direct, quantitative and non-invasive observation of localized stray magnetic field fluctuations at the surface of ferromagnetic materials in the presence large external bias fields. In order to further improve the range of applications and performance of the RT-SHPM, we are currently working on the fabrication of Hall probes with a higher spatial resolution and the incorporation of magnets for applying external fields greater than one Tesla.

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