

Scanning Hall probe microscopy of ferromagnetic structures

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Abstract

A state-of-the-art scanning Hall probe microscope (magnetic field sensitivity: spatial resolution: $30 \text{ nT}/\sqrt{\text{Hz}}$: $0.8 \mu\text{m}$ – $300 \text{ nT}/\sqrt{\text{Hz}}$: $0.25 \mu\text{m}$) has been used to image a range of ferromagnetic media. The technique is non-invasive and yields quantitative profiles of the stray fields near the sample surface as illustrated by images of a standard magnetic reference sample, permalloy nanostructures and colossal magnetoresistive perovskites. Rapid scanning (~ 1 frame/12 sec) has also been used to study the domain reversal in a thin Ni film. © 1999 Published by Elsevier Science B.V. All rights reserved.

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1. Main text

A number of techniques have been developed to characterise the magnetic properties of ferromagnetic materials. However, methods such as transmission electron microscopy (TEM) and magnetic force microscopy (MFM) require either extensive sample preparation or do not yield direct quantitative measurements of surface field profiles. We have therefore developed a scanning microscope system incorporating a non-invasive Hall sensor to investigate quantitatively the magnetic properties of ferromagnetic structures.

The scanning Hall probe microscope system (SHPM) [1] is based around an electron beam lithographically patterned sub-micron Hall probe fabricated from

a GaAs/AlGaAs two-dimensional electron gas (2DEG) mounted on the piezotube of a custom manufactured low-temperature scanning tunnelling microscope (STM). An integrated STM tip close to the Hall sensor region is used to position the Hall probe just above the surface of the sample. The sensor is then raster scanned over the sample surface, simultaneously measuring the normal component of the magnetic field and (optionally) the sample topography.

Fig. 1(a) shows a SHPM scan (obtained with a $0.8 \mu\text{m}$ sensor at 77 K) of a magnetic imaging reference sample (MIRS) [2] which is conventionally used to characterise the tip magnetisation of a MFM. The sample is a high-density storage disk on which a complex bit track has been recorded with a repeat distance $\sim 10 \mu\text{m}$. The basic elements of the bit track are clearly visible in this image although some information has been lost due to the relatively low spatial resolution of the sensor used. Fig. 1(b) shows the sample topography which was recorded simultaneously over approximately the same scan

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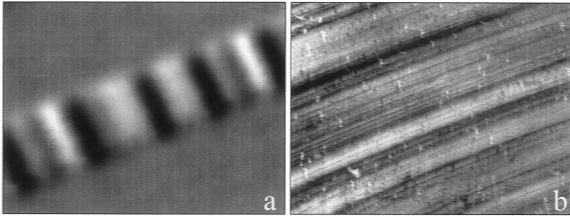


Fig. 1. SHPM images ($15.5 \mu\text{m} \times 11.7 \mu\text{m}$) of the MIRS sample at 77 K. (a) magnetic image (gray-scale spans ~ 130 G) (b) simultaneous STM image (gray-scale spans ~ 100 nm).

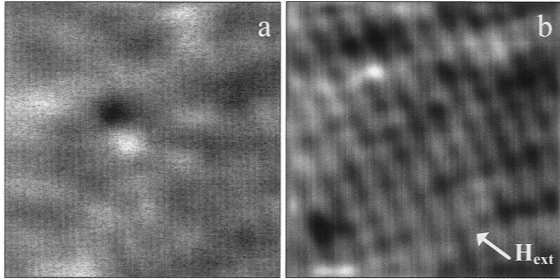


Fig. 2. Magnetic images ($23 \mu\text{m} \times 23 \mu\text{m}$) of a hexagonal array of $\text{Ni}_{0.8}\text{Fe}_{0.2}$ permalloy nanostructures at 77 K: (a) $H = 0$, (b) $H = 80$ Oe (gray-scale spans ~ 0.57 G).

area. This STM scan clearly reveals striping due to laser texturing performed prior to recording to achieve a smoother surface. Both the magnetic and topographic SHPM results compare favourably with MFM and AFM images of the same sample.

Fig. 2 shows SHPM images of an array of $\text{Ni}_{0.8}\text{Fe}_{0.2}$ permalloy nanostructures obtained with a $0.8 \mu\text{m}$ Hall sensor at 77 K. Electron beam lithography was used to pattern approximately circular structures (400 nm in diameter and 50 nm thick) which were arranged in a hexagonal lattice with $2 \mu\text{m}$ periodicity. In the absence of an applied field we see very little field corrugation across the sample (Fig. 2a) indicating that most of the dots contained two or more domains with very weak quadrupole (or higher order) field distributions. Upon application of an in-plane field ($H \sim 80$ Oe) nearly all the dots seem to assume a single-domain configuration (Fig. 2b). The stripe pattern that runs nearly diagonally across the image has approximately a $2 \mu\text{m}$ period and lies along one of the principal axes of the underlying hexagonal lattice. The dipoles are tilted with respect to this axis in the direction of the applied field giving the magnetic image its distinctive appearance.

Fig. 3 shows some preliminary measurements on a colossal magnetoresistive (CMR) perovskite film [3]. The sample consists of a 300 nm $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$ film on a sapphire substrate and had a broad resistivity versus

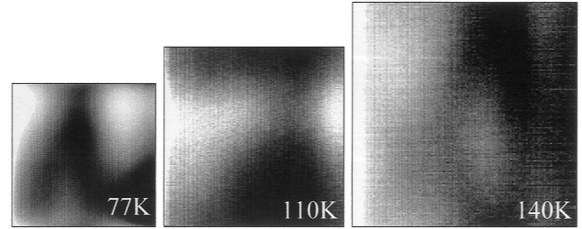


Fig. 3. SHPM images of a 300 nm CMR film at various temperatures. (a) 77 K, $23 \mu\text{m} \times 23 \mu\text{m}$ (gray-scale spans ~ 0.56 G) (b) 110 K, $29 \mu\text{m} \times 29 \mu\text{m}$, (~ 1.69 G) (c) 140 K, $36 \mu\text{m} \times 36 \mu\text{m}$, (~ 4.18 G).

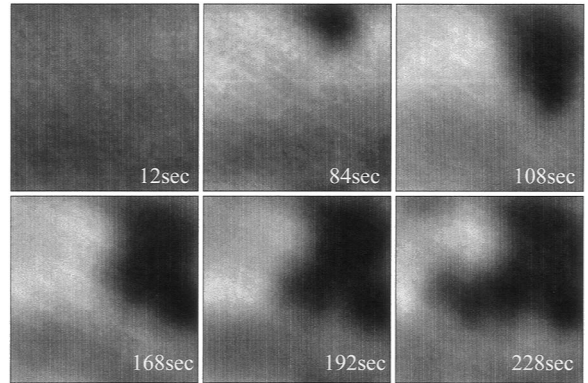


Fig. 4. Quasi-real time images ($23 \mu\text{m} \times 23 \mu\text{m}$) of domain reversal in a thin Ni film. (gray-scale spans ~ 1 G). Each frame took 12 s to acquire and was at the indicated times.

temperature dependence which peaked at 216 K, separating the paramagnetic (high T) and ferromagnetic (low T) regimes. Fig. 3 shows the SHPM images ($0.8 \mu\text{m}$ Hall sensor) of approximately the same region of the sample at three different temperatures (77, 110 and 140 K) on the ferromagnetic side of the resistivity peak. We see a marked change in the domain structure of the sample as the temperature is reduced with a pronounced reduction in the magnitude of the stray fields. AFM scans on similar samples show the grain size of the film to be small ($< 1 \mu\text{m}$) and indicates that the domain structure we measure extends over many grain boundaries. Future work will attempt to establish a direct correlation between microscopic domain structure and resistance/magnetoresistance measurements.

Finally, Fig. 4 presents results tracing the time evolution of domain reversal at 77 K in a thin nickel film exhibiting perpendicular magnetic anisotropy (PMA) [4]. The sample consists of a 5 nm Ni film on a 200 nm Cu buffer layer (Si substrate) with a 3 nm protective Cu cap. Misfit strain between the Ni and Cu buffer layer are believed to cause the PMA. The sample was initially in its remanent magnetic state after the removal of a saturating

field. A magnetic field of 236 Oe, just sufficient to initiate domain reversal ($H_c \sim 230$ Oe), was then suddenly applied in the opposite sense and maintained. The Hall sensor was then repeatedly scanned over the same region of the sample (scan rate ~ 1 image every 12 s). Frame 1 shows the sample in its virgin state ($t = 12$ s) while successive frames shows a reverse (dark) domain propagating into the scan field. Domain growth did not occur smoothly in time. Initially, the dark domain was seen to grow steadily (up to 108 s), however then remained pinned for approximately 1 min. The domain then advanced once more, progressing further into the scan field and was still migrating through the sample more than 7 min after the magnetic field was initially applied to the sample.

In conclusion, we have illustrated the potential of the SHPM as a high-resolution imaging technique for mag-

netic media. A wide range of operational temperatures and applied magnetic fields also allow the instrument to investigate samples under demanding conditions. We believe that these advantages could well establish the SHPM as a standard imaging tool in the near future to complement existing imaging techniques.

References

- [1] A. Oral, S.J. Bending, M. Henini, *Appl. Phys. Lett.* 69 (9) (1996) 1324.
- [2] P. Rice, S.E. Russek, J. Hoinville, M.H. Kelley, *IEEE Trans. Magn.* 33 (1997) (5) (Pt2) 4065.
- [3] Q.Y. Lu, C.C. Chen, A. DeLozanne, *Science*, 276 (1997) (5321) 2006.
- [4] P. Rosenbusch, J.Y. Lee, G. Lauhoff, J.A.C. Bland, *J. Magn. Mater.* 172 (1-2) (1997), 19.