Size and Self-Field Effects in Giant Magnetoresistive Thin-Film Devices

R. William Cross, S. E. Russek, and S. C. Sanders
Electromagnetic Technology Division, National Institute of Standards and Technology
Boulder, Colorado 80303

M. R. Parker, J. A. Barnard, and S. A. Hossain
Center for Materials for Information Technology, University of Alabama
Tuscaloosa, Alabama 35487

***Abstract* —Giant magnetoresistance (GMR) was measured as a function of device size for patterned NiCoFe/Cu and NiFe/Ag films. For the quasi-granular NiCoFe/Cu films, the normalized maximum change in resistivity $\Delta\rho/\rho$ was 8% for most of the samples. For the NiFe/Ag films, antiparallel alignment was achieved through magnetostatic coupling, not exchange fields, with a $\Delta\rho/\rho$ of 4.5%. The films were patterned into stripes with Au current leads for size-effect measurements. The height of the stripes varied from 0.5 to 16 μm and the track width varied from 1 to 16 μm. Discrete switching events and anomalous low-field dips in the response were observed for both materials for small device sizes. Self-field and heating effects due to the applied current were investigated for the NiFeCo/Cu films. The effect of the self-field produced by the applied current was separated from the thermal contribution and was found to reduce the response by over 32% for a current density of 10^7 A/cm^2.**

INTRODUCTION

Over the last few years, giant magnetoresistance (GMR) materials have received a lot of attention from the magnetic recording industry as possible candidates for new magnetoresistive (MR) read-head materials. These new materials potentially could increase the signal-to-noise ratio by a factor of 10 compared to existing MR technology. Some of the important parameters for evaluating GMR materials for read-head applications are the normalized change in resistance $\Delta R/R$, the field needed to saturate the response, size effects due to demagnetizing fields and discrete switching events, and the effect of large applied current densities. In this work, we focus on the measurement of these parameters in NiCoFe/Cu and NiFe/Ag multilayers.

The devices were measured as a function of size to determine the effect of magnetostatic fields and individual switching events on the response. As the device becomes smaller, the response broadens and individual switching events are observed as jumps in the response (Barkhausen noise). These jumps are detrimental for using granular/discontinuous multilayers as read-head sensors. The response was also measured as a function of the applied current density to determine the effect of the self-field produced by the applied current. After separating thermal effects, the self-field effect was found to reduce the response by over 32% for current densities typically used in MR read heads.

Manuscript received April 14, 1994. Contribution of the National Institute of Standards and Technology, not subject to copyright.

EXPERIMENT

The exchange coupling between the grains in a given layer was broken or reduced in both materials by annealing or interdiffusion during deposition. The two different materials were studied because they both have low saturation fields compared to continuous multilayer systems and promise high sensitivities in the field range needed for read heads.

The NiCoFe/Cu GMR films consisted of 8 or 10 sputtered bilayers. The copper layers were 2.3 to 2.5 nm thick and the alloy layers were approximately 1.2 to 1.5 nm thick. After deposition, the microstructure of these films is thought to be granular due to interdiffusion of the magnetic material into the Cu. Low angle diffraction measurements indicate very poor multilayer structure [1]. The layers were deposited in the presence of an applied field to give an easy axis, which slightly reduces the hysteresis.

The films were fabricated into devices with Au current leads, and track widths, defined as the distance between the Au leads, varied from 1 to 16 μm. The width of the stripe was typically 8 times the track width. The height of the stripes varied from 0.5 to 16 μm. The active area of the device is defined as the stripe height times the track width, which is shown in Fig. 1(a).

The NiFe/Ag films were made following the original prescription outlined in [2]. The films consisted of 7 sputtered bilayers with a 4.4 nm layer of Ag and a 2 nm layer of $Ni_{82}Fe_{18}$. The films were annealed at 340°C for 5 minutes to obtain a $\Delta R/R$ of 4.5%. The thickness of the Ag layer is such that the layers are not exchanged coupled. The microstructure has been studied in detail by Parker et al. using SEM and cross-sectional TEM, and they determined that Ag bridges form during the anneal through the NiFe grain boundaries [3]. This is important in the NiFe/Ag multilayers because magnetic poles can form along the edges of the grains and couple by magnetostatic fields to grains in adjacent layers, producing antiparallel alignment [2]-[4]. The films were then patterned into the same device geometry as were the NiCoFe/Cu films. A four-probe resistance measurement in combination with two orthogonal field sources was used to measure the GMR response. The voltage probes contacted the Au current pads separately to eliminate lead resistance. Device resistance was typically 10 Ω. A maximum negative transverse field was applied, swept to positive field, and then back to negative field.

0018-9464/94$4.00 © 1994 IEEE

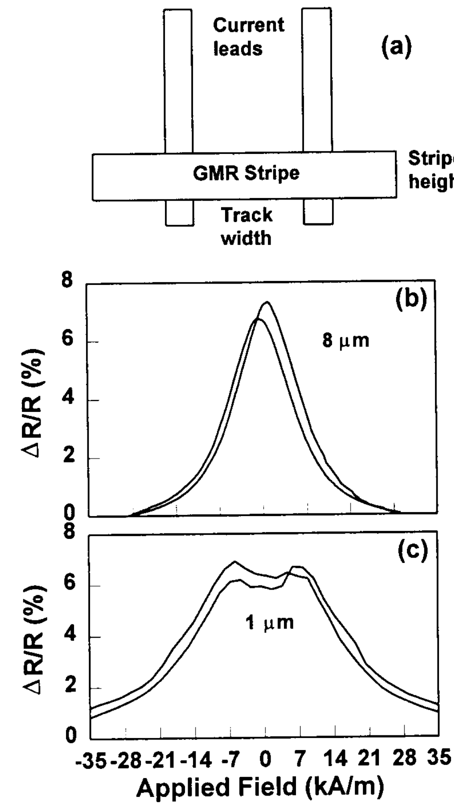

Fig. 1. (a) Schematic diagram of test devices. Plots of ΔR/R for (b) 8 × 16 μm and (c) 1 × 2 μm active area NiCoFe/Cu device.

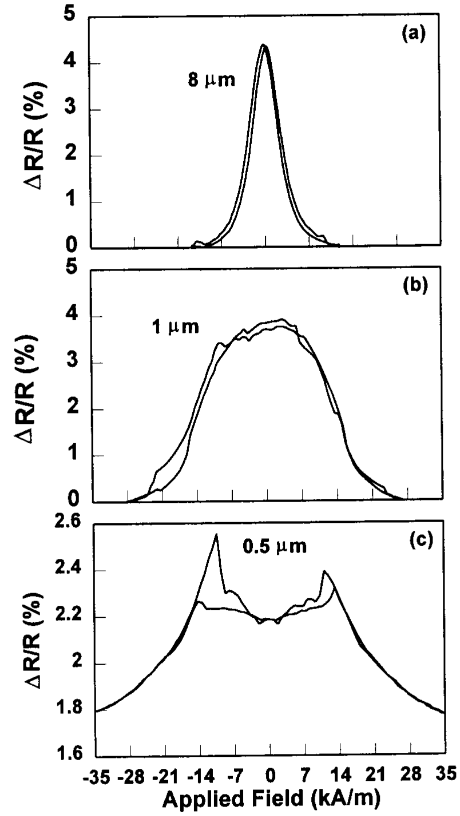

Fig. 2. Plots of ΔR/R for (a) 8 × 16 μm, (b) 1 × 2 μm, and (c) 0.5 × 1 μm active-area NiFe/Ag device.

RESULTS

A. Size Effects

The response as a function device size is shown in Fig. 1 for an 8 bilayer NiCoFe/Cu film. For all of the small devices, the maximum ΔR/R was determined using a high-field electromagnet and a two-probe measurement so that the response could be saturated. The measurements were then taken on the higher-resolution four-probe system. The response of the device with an active area of 8×16 μm is fairly smooth and narrow, with a half-width field of 4.8 kA/m (60 Oe) and a ΔR/R of nearly 8%. The response did not change greatly when the applied field was rotated up to 15° from the transverse direction in the plane of the film. Barkhausen jumps due to misalignment of the applied field, evident in conventional NiFe MR heads [5], were not produced as the field was rotated.

The response of the 1×2 μm active-area device is much broader compared to the 8 μm device. Transverse demagnetizing fields decrease the sensitivity of the device as the stripe height decreases (thickness is constant). At low fields, the curve is no longer parabolic and smooth like the 8 μm device, but rather it has an anomalous dip around zero field. This suggests that not all of the magnetic grains have aligned to an antiparallel state at zero field to obtain the maximum ΔR/R. Intergrain interactions may become important for the small sizes.

Similar measurements were performed on the NiFe/Ag films and are shown in Fig. 2. The response of the 8×16 μm device is smooth with a half-width field of 1.6 kA/m (20 Oe) and a ΔR/R of 4.5%. As was the case for the NiFeCo/Cu films, the response broadens with smaller stripe-heights. Discrete jumps are observed for the 1 μm stripe-height device and become pronounced for the 0.5×1 μm device. The response is reversible at high fields and has an anomalous dip near zero field with a reduction in ΔR/R. The curve is typical of what we observe for sub-micrometer devices. The discrete jumps in the response may severely limit the usefulness of these materials.

B. Self-Field Effects

For read-head applications, the applied current density through the GMR film can be as high as 2×10^7 A/cm^2 to obtain adequate signal levels and for biasing. The response of

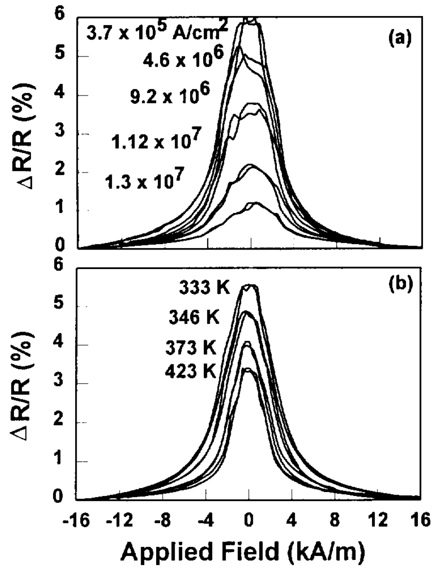

Fig. 3. Plots of GMR response as a function of (a) applied current density and (b) temperature for a NiCoFe/Cu device with a 6×6 μm active area.

the test devices was measured as a function of increasing current density in order to determine the effect of heating and self-fields due to the high current densities. The GMR response with increasing current is shown in Fig. 3(a) for a 10 bilayer NiCoFe/Cu device with a 6×6 μm active area. The normalized response ΔR/R decreased over 50% for a current density of 10^7 A/cm^2. The reduction was reversible up to 1.12×10^7 A/cm^2.

Included in the reduction of the response with current is the contribution of sample heating as the current increases, which increases the resistance R and slightly decreases ΔR. To separate the effect of sample heating, the response was measured at low current density as a function of temperature by heating a copper block attached to the device. The response as a function of temperature for a current density of 1.2×10^5 A/cm^2 is shown in Fig. 3(b); it is reversible up to 423 K, at which point the sample begins to anneal. Note that the response becomes slightly narrower with increasing temperature.

The reduction due to thermal effects can be separated from the self-field effect by measuring the resistivity at high field as a function of temperature for a low current density [Fig. 3(b)]. At fields large enough to saturate the magnetization, the self-field does not affect the response, so heating effects can be separated from the self-field effects. By measuring the resistivity at high field for increasing current density [Fig. 3(a)], the temperature of the device at the given current density can be determined from the resistivity versus temperature data. The result of doing this is shown in Fig. 4, where ΔR/R is plotted as a function of increasing temperature. The current curve includes both the self-field and thermal effects and the thermal curve includes only sample heating.

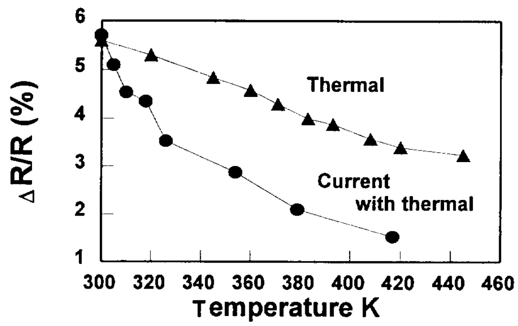

Fig. 4. Plots ΔR/R as a function of temperature for a NiCoFe/Cu device with a 6×6 μm active area. The difference between the curves is the self-field effect..

The difference between the two curves is the effect of the self-field. A current of 1.12×10^7 A/cm^2 heats the device to 418 K, corresponding to a self-field reduction of 32% of the response.

The broadening of the response near the peak with increasing current density is also due to self-field from the current. As seen in Fig. 3(b), the response would narrow with heating. The field from the current partially aligns the spins transverse to the stripe length, causing the reduction and broadening of the response. This transverse field component from the applied current actually points in opposite directions above and below the center of the film; this causes a reduction rather than just biasing the response.

Conclusions

Read-head test devices were made out of NiCoFe/Cu and NiFe/Ag thin films. These materials were measured and evaluated for potential use as MR read heads. Both materials experience individual switching events, observed as jumps and dips in the response. Magnetic fields due to the applied current were found to reduce the response by 32% for 1.12×10^7 A/cm^2, after separating the contribution due to device heating.

References

[1] S. Hossain, D. Seale, G. Qiu, J. Jarratt, J. A. Barnard, H. Fujiwara, and M. R. Parker, "Hysteresis reduction in NiFeCo/Cu multilayers exhibiting larger low-field giant magnetoresistance," J.Appl. Phys. vol. 75, pp. 7067-7069, 1994.

[2] T. L. Hylton, K. R. Coffey, M. A. Parker, and J. K. Howard, "Low field giant magnetoresistance in discontinuous magnetic multilayers," J. Appl. Phys. vol. 75, pp. 7058 - 7060, 1994.

[3] M. A. Parker, T. L. Hylton, K. R. Coffey, and J. K. Howard, "Microstructural origin of giant magnetoresistance in a new sensor structure based on NiFe/Ag discontinuous multilayer thin films," J. Appl. Phys. vol. 75, pp. 6382 - 6384, 1994.

[4] J. C. Slonczewski, "Magnetostatic mechanism for field-sensitivity of magnetoresistance in discontinuous magnetic multilayers," J. Magn. Magn. Mater. vol. 129, pp. 123- 128, 1994.

[5] R. W. Cross, A. B. Kos, C. A. Thompson, T. W. Petersen, and J. A. Brug, "Local magnetoresistive response in thin-film Ni-Fe read elements: A sub-micrometer-resolution measurement system," IEEE Trans. Magn. vol. 28, pp. 3060 - 3065, 1992.