High Current Density Self–Field Effects and Low-Frequency Noise in NiFe/Ag GMR Multilayers

L. S. Kirschenbaum, C. T. Rogers, P. D. Beale
Condensed Matter Laboratory, University of Colorado, Boulder, CO 80309-0390

S. E. Russek, S. C. Sanders
Electromagnetic Technology Division, National Institute of Standards and Technology, Boulder, CO 80303-3328

Abstract—**High current densities (10^6-10^7 A/cm^2) produce magnetic fields which can induce antiparallel magnetic alignment in large (16 μm and 8 μm) NiFe/Ag thin film multilayer devices. We induce GMR in unannealed devices which normally do not display GMR. We find multiple peaks in the magnetoresistance curves of annealed and unannealed devices. Analysis of the positions and shapes of these magnetoresistance peaks provides a new set of tools for determining the micromagnetic structure of the multilayers. Our magneto-optical Kerr effect data and low frequency noise data correlate with the magnetoresistance peaks and may yield further information about layer-layer interactions and domain structure.**

INTRODUCTION

We have found a number of hitherto unreported effects of high-current densities: the inducement of giant magnetoresistance (GMR) in unannealed NiFe/Ag multilayers, the appearance of multiple resistance peaks in the MR trace, and the appearance of 1/f-type noise coincident with the MR peaks. High current densities (~10^7 A/cm^2) in multilayers may be required for technological application of GMR devices to increase the detected voltage for a given magnetoresistance (MR) change. Also, in recent work the MR response of micrometer-sized devices has been found to broaden with large bias currents [1], while device specific MR structures were suppressed.

EXPERIMENT

Our multilayers are fabricated from $Ni_{82}Fe_{18}$ (2.0 nm)/Ag (4.4 nm) films grown on Si/SiO_2/Ta substrates using sputter deposition and are capped with 15 nm of Ta. Growth specifics are described in detail in [2] and are similar to the process developed by Hylton *et al.* [3] Some devices were annealed at 340°C in 5% H_2-Ar for 5 min. All data presented in this paper were taken on 16 μm, 10-square; 8 μm, 20-square; and 8 μm, 4-square devices in a four-terminal geometry where the magnetic stripe is at least 50% longer than the active region. Magnetoresistance (MR) curves were taken with applied DC bias currents ranging from 0 to 70 mA (2 × 10^7 A/cm^2 for 8 μm device width) and an AC excitation current of 10 μA at 2 kHz. A maximum magnetic field of 32 kA/m (~400 Oe) in the plane of the films and perpendicular to the device strip and bias currents was used. The capping Ta layer was removed by Ar^+ milling from some devices to facilitate optical penetration for magneto-optical Kerr effect (MOKE) measurement. The MOKE data were obtained with p-polarized 632 nm light incident at 60° in the p-transverse geometry. A 430 Hz, 80 A/m (1 Oe) excitation magnetic field parallel to the constant applied field was applied to the device to enable lock-in detection of the MOKE signal: the measured MOKE signal is actually proportional to dM/dH or χ. Devices were allowed to stabilize at a set temperature and bias current for 20 to 30 min before MR curves were obtained.

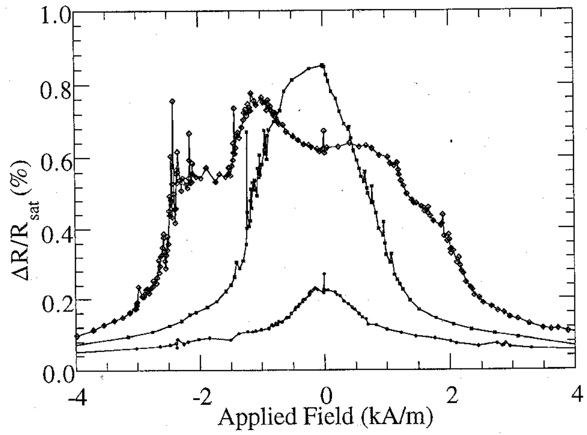

Fig. 1. Magnetoresistance curves from an 8 μm 4-square 5-layer unannealed device. The lowest curve was taken with no current bias, the next curve with a bias of 20 mA and the broadest curve with 50 mA. The 20 mA biased curve illustrates the inducement of GMR by application of high current density.

RESULTS AND DISCUSSION

Fig. 1 shows the MR response of an 8 μm, 4-square, 5-layer unannealed device for several different bias currents. This figure exemplifies all of the effects we have observed: inducement of GMR in unannealed devices, broadening of the MR response with bias current, the appearance of peaks at high current densities, and noisiness in the resistance near these resistance peaks. The unbiased curve shows a response $\Delta R/R_{sat}$ = 0.22% and is smooth. Application of a bias cur-

Manuscript received March 4, 1996.
L. S. Kirschenbaum, e-mail Leif.Kirschenbaum@Colorado.Edu
This work supported in part by the NIST PREP program.

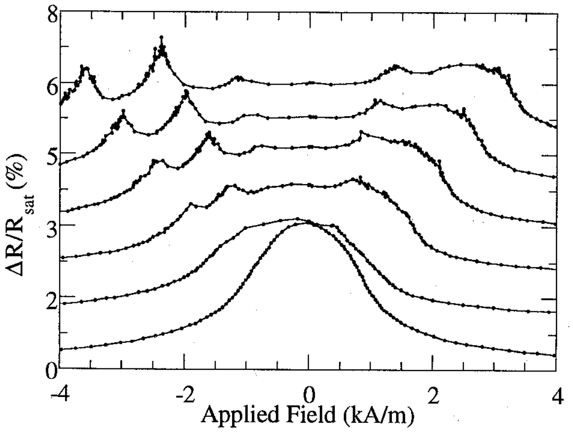

Fig. 2. Magnetoresistance curves from a seven-layer annealed 8 μm 10-square device. The bottom trace was taken with no bias current; proceeding upwards, the bias current increases by 10 mA per trace. Each trace is offset by 1% from the preceding one. Note that the magnetoresistance peak positions shift linearly with bias current.

rent of 20 mA (8×10^6 A/cm^2) to this device increased its response to 0.85% with a sensitivity $1/R_{sat} dR/dH$ of 0.005/(kA/m) (0.06/Oe). Increasing the bias current to 50 mA (2×10^7 A/cm^2) decreases the response to 0.62%, broadens the response even further, and introduces structure into the MR response. The behavior resulting from application of high current density is reversible and reproducible up to ~5×10^7 A/cm^2 at which current density irreversible changes occur. In Fig. 1 there are four structures in the magnetoresistance, for this five-layer device: two to the left of zero applied field, and two to the right. We have also observed the introduction of GMR in a 16 μm, 10-square device; the response increased from 0.42% to 1.0% with the application of a 50 mA (10^7 A/cm^2) bias current.

The six curves in Fig. 2 constitute a family of MR curves versus bias current for an 8 μm, 20-square, 7-layer *annealed* device, to show the progressive appearance of MR peaks at high bias. Proceeding vertically upward, each curve represents an increase in bias current of 10 mA. The MR response broadens as the bias current is increased; the maximum in bias current displayed for the 8 μm device, 50 mA, corresponds to a current density of 1.4×10^7 A/cm^2 in this device. The lowest curve shows GMR due to magnetostatic interactions [4], whereas the highest MR curve's shape is dominated by the self-field induced magnetic layer alignment. Seven structures may be identified in the highest bias current MR trace: three peaks to the left of the small bump at zero applied field, and three structures to the right (although the two outermost peaks are overlapped, seven peaks are evident when we fit the MR trace with seven Lorentzians). We find that the MR traces are similarly affected for 16 μm devices and that high current densities in 16 μm and 8 μm annealed devices do not cause irreversible changes in these devices.

The peaks' positions shift linearly with the bias current density above ~8×10^6 A/cm^2. This linearity suggests that the peaks arise from a current-induced magnetic field effect inside the multilayer structure. We have produced a simple micromagnetic model for the behavior of these multilayers [5]. Briefly, by using an estimation of the current densities J in each layer, we can estimate the values of H_I, the current-induced self-field[6]: $H_I \approx Jz/2$, where z is the distance from the middle of the multilayer to the layer of interest. We write an equation which balances the current-induced self-field, external field, magnetostatic field, and local layer-layer coupling. This equation manifests a balance at an external field which is linearly proportional to the current-induced self-field (and hence the current) but has a nonzero intercept at zero bias current due to the various other terms.

Using our model we are able to estimate layer-layer interaction fields of 0.6-0.8 kA/m (8-10 Oe). This interaction field is due mainly to the layer-layer local coupling term J_0/μ. Using a value for $\mu \approx 1 \times 10^{-17}$ J/T ($\approx 1 \times 10^6 \times \mu_B$, where μ_B is the Bohr magneton) derived from temperature dependent peak widths and the J_0/μ value of 0.8 kA/m, we estimate an interlayer coupling strength of 1×10^{-20} J (0.07 eV $\approx 3\, k_B T_{room}$).

Revisiting Fig. 1 in the context of current-induced self-fields, we hypothesize that the self-fields cause the creation of antiferromagnetic interfaces within the multilayer stack. This explains the induced GMR in unannealed multilayers which we observe with the application of high current densities. At low current densities, the self-fields are not strong enough to overcome the local random fields in the magnetic layers; the higher-current-density self-fields are strong enough to be comparable with the random fields and overcome them, causing some antiferromagnetic interfacing within the multilayer. Even higher current densities (50 mA in Fig. 1) align the magnetic layers so strongly that only one antiferromagnetic interface exists, causing a decrease in the net MR response, as is shown in Fig. 1, and the appearance of multiple peaks in the MR. We estimate the random fields' magnitude in the 5-layer multilayer as 0.5 kA/m (6 Oe) by assuming that the current-induced field produced by the 20 mA bias is on the order of the random internal fields.

We observe resistance peaks for internal magnetic layers in both annealed and unannealed 5- and 7-layer devices, and yet resistance changes are not expected to be caused by rotation of a magnetic layer sandwiched between two antiparallel magnetic layers[5]. We hypothesize that fluctuations in the magnetic layers cause peaks in resistance. In Figs. 1 and 2 we observe "spikiness" in the MR curves near the peaks in magnetoresistance, indicative of resistance noise near those peaks. Measurements of the 1 Hz resistance spectral noise are shown in Fig. 3 and are plotted along with the magnetoresistance for comparison with the resistance peak positions. The resistance noise, presumably due to layer magnetization fluctuations, increases substantially underneath two of the observed peaks, supporting a hypothesis that these resistance peaks are linked to layer magnetization fluctuation. The noise amplitude was too small to be observable under the resistance peaks at -0.2 kA/m and at positive external field.

Fig. 4 shows MOKE data from a 16 μm, 10-square, 7-layer

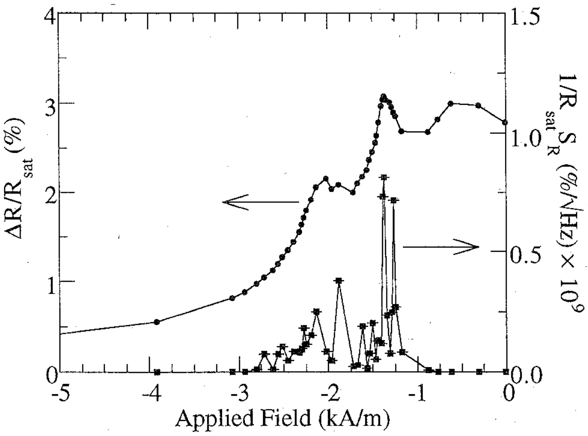

Fig. 3. Comparison of the resistance spectral noise amplitude at 1 Hz and magnetoresistance taken at 60 mA and 250 K for a 16 μm, 7-layer 10-square annealed device. Note the close correlation between resistance peaks and regions of increased noise.

annealed device. The MOKE signal is proportional to the magnetic susceptibility and is maximal when the topmost magnetic layer is free to rotate since most of the incident light does not penetrate deeper than this layer. Fig. 4 (a) shows the MOKE and magnetoresistive response for zero bias. Fig. 4 (b) shows the response with a bias of 70 mA (9.8 × 10^6 A/cm^2). The MOKE signal peaks at -2.28 kA/m (28.7 Oe). Given the applied current density, we would expect a resistance peak at 0.95 kA/m (11 Oe), but this is not resolvable due to poor resistance peak separation at this current density. The difference in field between the expected field position of 0.95 kA/m and the Kerr maximum at 2.28 kA/m is presumably due to the finite interlayer coupling J_0/μ_i, which we estimate as 1.34 kA/m (17 Oe), larger than the finite field intercept measured in the 8 μm device. We also note the existence of a resistance structure at -1.7 kA/m (21 Oe), which appears to have a corresponding shoulder in the Kerr signal, presumably due to optical interaction with the second magnetic layer. These measurements confirm that the outer layer is not susceptible to magnetic motion until the external field is sufficient to overcome the net internal bias and exchange fields.

CONCLUSION

NiFe/Ag multilayers can demonstrate a variety of interesting behaviors when biased at high current densities. We have observed the inducement of GMR in unannealed samples, which normally do not show large MR response. Peaks appear in the MR traces at high curent densities, and shift linearly with the applied current. Analysis of these peak positions and widths yields a number of interesting micromagnetic quantities. Our hypothesis [5] that the peaks in resistance are linked to fluctautions in the layers' magnetizations is supported by the increased noise and magnetic susceptibility measured under these peaks, indicating that micromagnetic models may need to take fluctuations into account when describing the magnetoresistance of discontinuous multilayers.

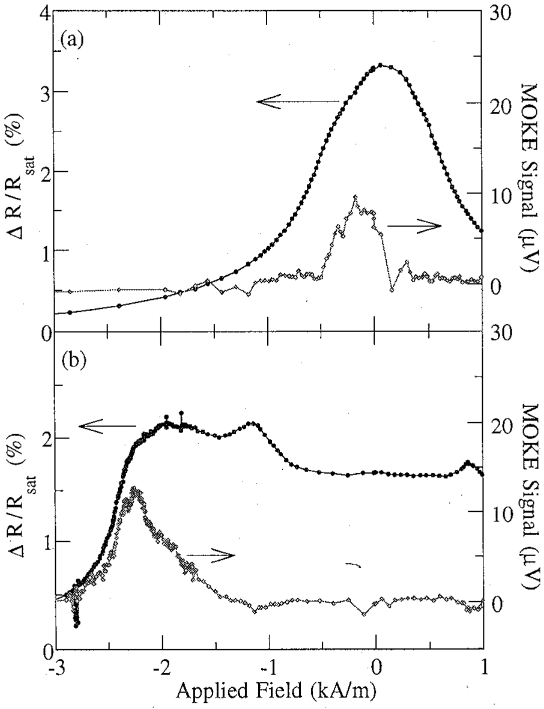

Fig. 4. Comparison of the MOKE signal and MR response of a 16 μm 7-layer 10-square annealed device biased at 0 and 70 mA. (Figs. (a) and (b) respectively) Note that the MOKE signal, which is proportional to the magnetic susceptibility, is a maximum at the point where the outermost layer is presumably the most active. In (b) the Kerr signal peaks at -2.28 kA/m, in disagreement with the theoretical self-field of 0.95 kA/m at the outermost layer.

REFERENCES

[1] S. E. Russek, R. W. Cross, and S. C. Sanders, "Size effects in submicron NiFe/Ag GMR devices," *IEEE Trans. Magn.* **31**, (6) (1995).

[2] Y. K. Kim and S. C. Sanders, "Magnetostriction and giant magnetoresistance in annealed NiFe/Ag multilayers," *Appl. Phys. Lett.* **66**, 1009 (1995).

[3] T. L. Hylton, K. R. Coffey, M. A. Parker, and J. K. Howard, "Giant magnetoresistance at low fields in discontinuous NiFe-Ag multilayer thin films," *Science* **261**, 1021 (1993).

[4] J. C. Slonczewski, "Unusual magnetoresistive response of process-controlled Ag/Permalloy bilayer thin films," *J. Magn. Magn. Mater.*, **129**, L123 (1994).

[5] L. S. Kirschenbaum, C. T. Rogers, P. D. Beale, S. E. Russek, and S. C. Sanders, "Bias current dependent peaks in NiFe/Ag giant magnetoresistance multilayer devices," *Appl. Phys. Lett.* **68** 3099 (1996).

[6] N. Smith, "Micromagnetics of GMR multilayer sensors at high current densities," *IEEE Trans. Magn.* **30**, (6) (1994).