Thermal annealing effects on low-frequency noise and transfer behavior in magnetic tunnel junction sensors

Xiaoyong Liu[a)] and Gang Xiao
Physics Department, Brown University, Providence, Rhode Island 02912

(Received 17 March 2003; accepted 21 August 2003)

We have investigated the low-frequency noise and transfer curve behavior in NiFe/AlO_x/NiFe magnetic tunnel junction sensors as a function of the annealing temperature. The magnetoresistance reaches a maximum of 35% with a maximal field sensitivity of 5%/Oe at an optimal annealing temperature of 170 °C. The origin of $1/f$ noise is explored by measuring the magnetic field dependence of noise at low frequencies. Our data indicate that samples annealed near this temperature exhibit $1/f$ noise that originates from magnetization fluctuations, whereas electronic noise due to charge trapping is dominant for other temperatures. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1617355]

Magnetic tunnel junctions (MTJs) have been extensively studied in last 10 years due to their potential application in nonvolatile memory and magnetic field sensing.[1–3] MTJ sensors have the potential to outperform giant magnetoresistance (GMR)-based spin-valve sensors due to their large magnetoresistance (MR), tunable resistance, high switching speed, and so on. So far, a great deal of effort has been put into optimizing sample fabrication to increase the MR ratio and reduce the resistance area ($R\times A$) product.[4,5] In addition to these characteristics, thermal stability is very important to guarantee that MTJs will be compatible with existing semiconductor technology. Previous studies have measured an increase in junction MR with an increase in annealing temperature up to a peak value of 200–300 °C for MTJs with IrMn exchange biasing layers. Above this annealing temperature, the MR ratio decreases due to interlayer diffusion.[6,7] For sensing applications, on the other hand, the ultimate detection sensitivity is limited by the intrinsic noise of devices, which is typically $1/f$ in nature at low frequencies.[8] It has been shown that $1/f$ noise in MTJ devices can generally be attributed to either electrical sources (field-independent charge trapping near or in the oxide barrier), or magnetic sources (field-dependent magnetization fluctuations).[9–12] But the relationship between $1/f$ noise and sample preparation parameters is still unclear, and there has been little research[13] into the effects of thermal annealing on MTJ sensor noise, even though annealing is widely implemented as part of the junction fabrication process. We have studied the magnetic field dependence of low-frequency noise in FeMn exchange biased MTJ sensors at different thermal annealing temperatures. Our results showed enhancement of sensor performance and reduction of $1/f$ noise over a narrow range of annealing temperatures. In this narrow range, noise is magnetic in origin and therefore is field dependent, while electrical noise due to charge trapping is the dominant source at other temperatures.

Our tunnel junctions were deposited via magnetron sputtering onto SiO_2 substrates in the following sequence: Pt (300 Å)/FeNi (30 Å)/FeMn (130 Å)/FeNi (60 Å)/Al_2O_3/FeNi (120 Å)/Al (490 Å). The alumina barrier was formed by oxidizing a thin layer of Al in oxygen plasma. The easy axis of the top "free" FeNi layer was defined by a 100 Oe dc field during sputtering. The samples were then patterned into cross geometries. Details of sample growth and fabrication are described elsewhere.[14] All the data presented here were from rectangular junctions with dimensions of $100\times 150\ \mu m^2$. Annealing was carried out in ambient conditions with a 40 min ramp up, followed by 10 min at the annealing temperature, and finally a 1 h cool down. During the thermal treatment, the junctions were submitted to a dc magnetic field of 1.6 k Oe along the easy axis.

The MTJ sensors were characterized in a probe station equipped with two pairs of electromagnets to produce magnetic fields in both the easy- and hard-axis directions. To achieve an orthogonal biasing configuration of free and pinned layers, a constant field of 6 Oe is applied along the hard-axis direction for domain stabilization. MR curves were measured using a four-probe method. Voltage fluctuations across the junction were measured by a spectrum analyzer in a magnetic shielding box. The typical measurement frequency range was 1–400 Hz. A cross-correlation method was employed to extract the sensor noise from unwanted background and system noise.

A typical plot of the magnetoresistance versus easy-axis magnetic field for junctions annealed at 170 °C is shown in Fig. 1(a). One can see that the region around 12.5 Oe is very steep, with minimal hysteresis. The biasing field along the hard axis is large enough to overcome the effective anisotropy field of the free layer.[15] Therefore, domain rotation dominates the MR response such that switching is coherent and reversible. This yields a nearly linear MR response with sensitivity, defined as the maximal slope in the linear region, of about 5%/Oe.

We have also measured the easy-axis field dependence of sensor noise. For a junction of large size, there will exist a large number of small fluctuators that contribute to the

[a)]Electronic mail: xiaoyong_liu@brown.edu

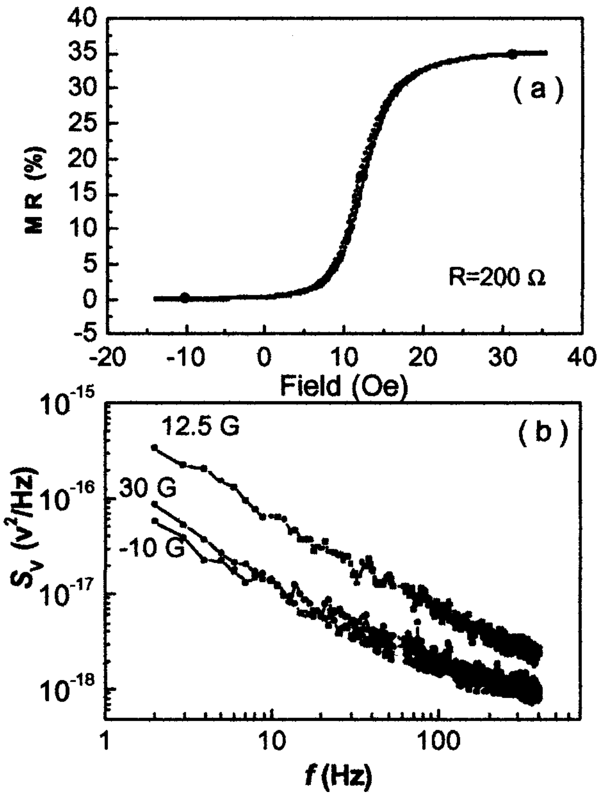

FIG. 1. (a) MR as a function of the field applied along the easy axis. (b) Noise power spectra at easy-axis fields of −10, 15, and 30 Oe, respectively.

voltage–time characteristics and superimposition of those independent fluctuators with a broad distribution of characteristic switching time scales will result in a $1/f$ noise spectrum.[8] Over the entire frequency range of our experiment, the noise spectra are $1/f$ in nature and scale as the square of the bias voltage up to 300 mV. The noise spectrum observed can be quantified by Hooge's formula: $S_v = \alpha V^2/Af$, where α is a material-specific parameter, and A is the area of the junction. Figure 1(b) gives some typical noise spectra S_v at different easy-axis magnetic fields. At fields of +30 and −15 Oe, corresponding to antiparallel and parallel states, respectively, the spectra are coincident but have some small differences. However, at 12 Oe, which is within the transition region of sensor response, the level of noise increases by an order of magnitude. This implies that the low-frequency noise of this sample is very sensitive to the magnetization state and is magnetic in origin.

The effect of thermal annealing on our MTJ sensor was systematically studied. Figures 2(a)–2(e) show the dependence on the annealing temperature of the junction resistance, tunneling magnetoresistance (TMR), MR sensitivity, low frequency noise extrapolated at 1 Hz, and magnetic field sensitivity, respectively. It is clear from Fig. 2 that as the annealing temperature ramps up from the as-deposited state to 240 °C, the junction $R \times A$ product drops monotonically. The observed decrease in resistance agrees with results for junctions with thicker barriers and is believed to be caused by changes in the structural properties of the junction as opposed to changes in the barrier itself.[6] The TMR of the sensor was highly dependent on the annealing temperature

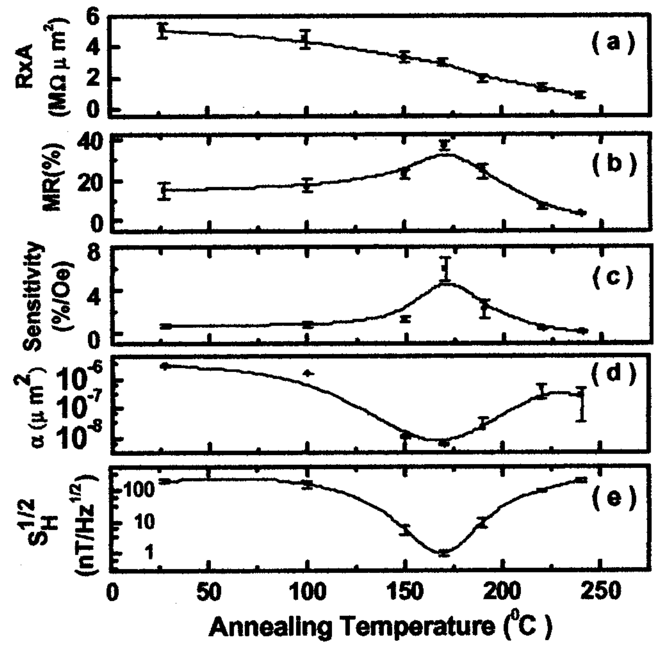

FIG. 2. Annealing temperature dependence of the (a) junction resistance, (b) TMR, (c) MR sensitivity, (d) normalized $1/f$ noise, and (e) magnetic field sensitivity $S_H^{1/2}$.

[Fig. 2(b)]: It more than doubles to ~36% from the original 15% upon annealing at 170 °C, then starts to decrease with a further increase of temperature. The sensitivity of the sensor also reaches its maximum value of 5%/Oe at 170 °C, and it decreases at higher and lower temperatures. Figure 2(d) gives the noise measurement results for the same set of samples. For ease of comparison, the data were normalized as $\alpha = fS_vA/V^2$. For samples as prepared, α is relatively high, and it drops abruptly at temperatures above 100 °C. At optimal annealing temperature of about 170 °C, α reaches its minimum, which is about two orders of magnitude lower than that of the as-deposited samples. There is a slight increase in noise with further increases in the annealing temperature. The ultimate performance of a sensor is affected by both the magnetoresistive sensitivity and the noise level. In order to better characterize our sensors, we define magnetic field sensitivity $S_H^{1/2}$ according to $S_H = S_v/V^2/(\partial R/R\partial H)^2$. It can be seen from Fig. 2(e) that $S_H^{1/2}$ exhibits a broad minimum around 170 °C due to the relatively high MR sensitivity and low noise level. The field sensitivity at this point is about two orders lower than that of the sample as deposited and reaches 1 nT/Hz$^{1/2}$. Based on the data shown above, it is clear that improved sensor performance with higher MR sensitivity and reduced noise levels can be achieved by annealing the samples in a small temperature region of about 170 °C.

We also studied the field dependence of $1/f$ noise at different anneal temperatures. Figure 3 shows representative results. For the samples annealed at 170 °C [Fig. 3(b)], there is a substantial increase of noise in the transition region, which reaches a maximum at $H = 12.5$ Oe, which corresponds to maximum MR sensitivity. Detailed studies showed a roughly linear relationship between noise and MR sensitivity.[15] This strong magnetic field dependence can be interpreted as the result of thermally assisted angular magne-

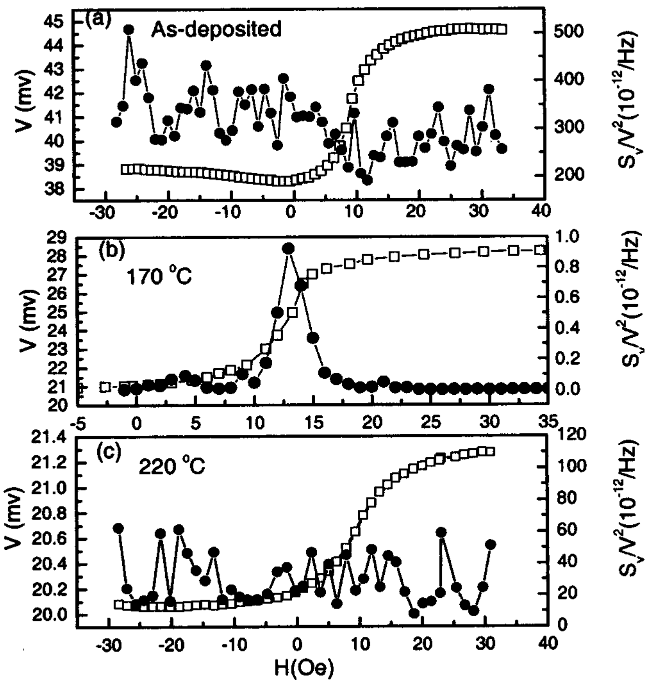

FIG. 3. MTJ sensor response (open circles) and noise level (closed squares) vs the easy-axis field applied for samples (a) as deposited and annealed at (b) 170 and (c) 220 °C. Note the difference in scale of the vertical axes.

tization fluctuations in the free layer.[9] On the other hand, for the samples as deposited and annealed at 220 °C [Figs. 3(a) and 3(c)], the overall noise level is at least one order of magnitude higher than that of samples annealed at 170 °C and roughly constant; there is no field dependence observed. These results imply that the origin of $1/f$ noise occurring in our MTJ sensors is different due to differing postthermal treatments.

The different field dependence of MTJ sensor noise at different annealing temperatures can be understood qualitatively as follows. Low-frequency noise of MTJs can be either electric or magnetic in origin; which source is dominant depends on the sample microstructure. For our samples as deposited, there may exist some defects and local inhomogeneties inside the tunnel barrier. These defects serve as sources for charge trapping, and lead to spin-independent resistance fluctuations, which show no field dependence. This also explains why low MR ratios occurred in those samples. It is known that defects can be removed by proper postthermal annealing, thus making the distribution of oxygen atoms more homogeneous across the barrier. Additionally, a smoother barrier would create a more uniform current distribution, thereby reducing the effects of a small number of noisy ‘‘hot spots’’ and lessening the electrical noise. With an adequately smooth barrier, electrical noise is reduced to a point where field-dependent magnetization noise becomes important, and eventually dominates. These magnetic fluctuations are spin dependent, and can be changed by external sensing fields, resulting in a sharp peak in the most sensitive region. The field independence and increase in noise when the annealing temperature is above 200 °C is, however, not fully understood. A possible explanation is that due to the poorer thermal stability of FeMn, interlayer diffusion shows up at relatively low temperatures, which in turn leads to less distinct interfaces and possibly more defects near or inside the oxide barrier. In our measurement, electrical noise is normally several orders of magnitude larger than that of magnetic noise. Field-dependent noise can only be seen in ‘‘clean’’ samples, i.e., samples with few defects, which also show the highest MR values. In our experience, such samples can be obtained by optimizing the sample growth conditions and proper thermal annealing reported here.

This work was supported by NSF through Grant Nos. DMR-0071770 and DMR-0074080.

[1] J. S. Moodera and G. Mathon, J. Magn. Magn. Mater. **200**, 248 (1999), and references therein.
[2] S. S. P. Parkin *et al.*, J. Appl. Phys. **85**, 5828 (1999).
[3] K. Ohashi *et al.*, IEEE Trans. Magn. **36**, 2549 (2000).
[4] X. F. Han, M. Oogane, H. Kubota, Y. Ando, and T. Miyazaki, Appl. Phys. Lett. **77**, 283 (2000).
[5] Z. G. Zhang, P. P. Freitas, A. R. Ramos, N. P. Barradas, and J. C. Soares, J. Appl. Phys. **91**, 8786 (2002).
[6] R. C. Sousa, J. J. Sun, V. Soares, P. P. Freitas, A. Kling, M. F. da Silva, and J. C. Soares, J. Appl. Phys. **85**, 5258 (1999).
[7] S. Cardoso, R. Ferreira, P. P. Freitas, P. Wei, and J. C. Soares, Appl. Phys. Lett. **76**, 3792 (2000).
[8] M. B. Weissman, Rev. Mod. Phys. **60**, 537 (1988).
[9] E. R. Nowak, M. B. Weissman, and S. S. P. Parkin, Appl. Phys. Lett. **74**, 600 (1999).
[10] E. R. Nowak, R. D. Merithew, M. B. Weissman, I. Bloom, and S. S. P. Parkin, J. Appl. Phys. **84**, 6195 (1995).
[11] S. Ingvarsson, G. Xiao, S. S. P. Parkin, W. J. Gallagher, G. Grinstein, and R. H. Koch, Phys. Rev. Lett. **85**, 3289 (2000).
[12] D. S. Reed, C. Nordman, and J. M. Daughton, IEEE Trans. Magn. **37**, 2028 (2001).
[13] K. S. Kim, H. J. Shim, I. J. Hwang, B. K. Cho, J. H. Seok, and J. Kim, J. Appl. Phys. **91**, 8804 (2002).
[14] X. Liu, C. Ren, L. Ritchie, B. Schrag, G. Xiao, and L. Li, J. Magn. Magn. Mater. (to be published).
[15] X. Liu, C. Ren, and G. Xiao, J. Appl. Phys. **92**, 4722 (2002).