Telegraph Noise in Silver-Permalloy Giant Magnetoresistance Test Structures

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Abstract—**We report noise data for discontinuous $Ni_{82}Fe_{18}/Ag$ multilayer test structures. Examination of the noise data for this material indicates that random telegraph fluctuator (RTF) noise of the resistance is the predominant noise source. Analysis of the RTF noise in these structures presents an opportunity to estimate magnetic domain or magnetic cluster strengths and the domain-domain interactions.**

INTRODUCTION

The detailed micromagnetic behavior of GMR multilayers is not yet well understood. Many of these systems suffer from Barkhausen resistance jumps and/or resistance fluctuations which may make them undesirable for device applications. Methods are needed to characterize the strengths, dynamics, and interactions of the magnetic domains present in these multilayers to help elucidate both their magnetoresistive mechanism and their Barkhausen noise characteristics.

Discontinuous multilayers, developed by Hylton et al. [1], are promising for magnetic field sensors due to their high sensitivities. These structures are formed by annealing $Ni_{82}Fe_{18}/Ag$ multilayers. Annealing causes silver to diffuse into grain boundaries and break up the exchange interaction within the magnetic layers. The weak magnetostatic interaction of the magnetic grains can lead to an antiferromagnetically correlated zero-magnetic-field state as described by the model of Slonczewski [2]. The weakness of the magnetostatic interaction, which is needed for high sensitivity at low magnetic fields, coupled with disorder due to shape anisotropy and variations in grain separation can lead to complicated domain structure. Noise analysis of these structures offers a method by which we may investigate their domain structure, interactions, and dynamics.

Although 1/f noise has previously been observed in GMR multilayers [3], in this paper we present the first data on noise due to thermally activated motion of *individual* domains in discontinuous multilayer GMR films. We demonstrate that noise data may provide information regarding domain moments and activation energies.

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EXPERIMENT

Our devices are fabricated from 44.8 nm thick $Ni_{82}Fe_{18}/Ag$ films grown on Si/SiO_2 substrates by using sputter deposition. The multilayers consist of alternating layers of Permalloy (2.0 nm) and silver (4.4 nm); growth specifics are described elsewhere [4]. The films are annealed at 340°C in 5% H_2-Ar ambient for 5 minutes and then photolithographically patterned into 0.7 to 16 μm stripes with two-terminal and four-terminal geometries.

A low frequency ($f \leq 100$ kHz) spectrum analyzer is utilized to acquire the voltage noise power spectral density of current biased (0.5 to 16×10^6 A/cm^2) structures. A single field coil provides a maximum magnetic field of 40 mT in the plane of the film perpendicular to the device strip and current.

RESULTS AND DISCUSSION

The inset of Fig. 1 is an example of a room temperature magnetoresistance (MR) curve of a 1.8 μm wide 1-square structure. The MR curve is not smooth and shows discrete Barkhausen jumps in the resistance. At these structure sizes each MR curve is unique in detail, although a magnetoresistance change of ~3% is typical.

The noise spectra of resistor structures with sizes ranging from 4 to 16 μm displayed roughly 1/f ($f \equiv$ frequency) character, with occasional weak structure. In this paper we discuss resistor structures with sizes in the 1 to 2 μm range.

Examination of these structures shows noise spectra that are distinctly Lorentzian in nature. Fig. 1 shows a voltage noise spectrum from the 1.8 μm device with a bias current density of 2.2×10^6 A/cm^2 (1.8 mA) taken at an applied field of 4.04 mT. The voltage across these devices as a function of time shows that the voltage power spectrum arises from two-level switching events. Subsequent statistical analysis of the up and down times of the voltage time traces reveals that the times in the two states are exponentially distributed, thus explaining the Lorentzian power spectral shape. The voltage across the structure as a function of time at two different temperatures is illustrated in Fig. 2. The voltage shows distinct two-level telegraph noise which is associated with fluctuations in the structure resistance; the associated resistance amplitude of these jumps is as large as 50 mΩ at room temperature, and 1 to 10 mΩ at 110 K. For convenience the two states will be called "up" and "down"

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states. As we discuss below, we hypothesize that the resistance switching arises from switching of individual magnetic domains in the device. We emphasize that over the entire measured range of temperature (4 to 300 K) and magnetic field strength (0 to 40 mT) that we have investigated, this type of exponentially distributed two level resistance switching is the dominant noise source.

At any given temperature and field, a given device may have zero, one, or several active switchers in the experimentally investigated bandwidth (10 mHz to 100 kHz). The specific details of switching rates and amplitudes can often be completely changed simply by brief excursions to a different field and/or temperature. We suggest that the changes are due to changes in magnetic domain configurations, some of which are permanent and some reversible. An example of this kind of sudden change in noise character is shown in Fig. 2. Here, a discrete increase in switching amplitude is seen with the step of temperature from 110 K to 111 K. The higher amplitude remained approximately constant until this fluctuator disappeared at 119 K. Upon decreasing the temperature neither the large nor the small amplitude fluctuator reappeared.

In principle the characteristic lifetimes of the two levels should provide insight into the energetics of domain reorientation. Details about local field strengths, domain magnetization, anisotropy energies, and temperature should all play a role. The sudden (and often irreversible) changes we observe in switching character have made it difficult to obtain systematic temperature and field dependence of the lifetimes. However, over limited field and temperature ranges we have been able to obtain data which broadly support a picture of thermal activation over temperature- and magnetic field-dependent barriers.

Since many previously observed two-level systems show thermally activated rates [5], we postulate an Arrhenius-like dependence of the states' characteristic rates:

$$\frac{1}{\tau}=\frac{1}{\tau_{0,U/D}}\exp\left[\frac{-\left(E_{1,(U/D)} \pm \mu_{U/D} \bullet \mathbf{H}\right)}{k_B T}\right], \tag{1}$$

where τ represents the lifetime of either the "up" (U) or "down" (D) state. Here, we postulate a temperature- and field-dependent activation energy. E_1 is a term dependent upon anisotropy and exchange, and $\mu\cdot\mathbf{H}$ is a Zeeman term. Both E_1 and μ may be temperature dependent. It should be noted that magnetic field-dependent lifetime data would then yield an effective magnetic moment for the domain or cluster of domains through the postulated $\mu\cdot\mathbf{H}$ dependence. In addition, temperature-dependent lifetime data would yield information regarding the characteristic frequency $1/\tau_0$ and any temperature dependence in E_1 and μ.

Careful stepping of the applied magnetic field allows us to measure the up and down state lifetimes of single fluctuators over a range of applied fields. Stepping the applied field away from the field value where a fluctuator has a 50-50 duty cycle causes one or both of the fluctuator's lifetimes to change. Too large a change in field or temperature causes the fluctuator to disappear, typically remaining unrecoverable. Fig. 3 illustrates the up and down times for a fluctuator at 105 K measured over an appreciable field range. In accordance with (1), the semilogarithmic plot of these lifetimes shows linear field dependence. We extract effective moments for the up and down times of $-4.17 \pm 0.83 \times 10^6\ \mu_B$ and $+3.19 \pm 0.67 \times 10^6\ \mu_B$, where μ_B is the Bohr magneton (determined by assuming $\cos\theta = 1$, i.e. these are lower bounds on μ). The observed field-dependent rates often yield moments on the order of $10^6\ \mu_B$. However, we have also observed cases where one time is field dependent ($\mu \approx 10^6\ \mu_B$) while the other time is not. The Permalloy "pancake" grains have approximate volumes of 1400 nm^3, containing approximately 1×10^5 atoms, or $\sim 1 \times 10^5$ spins. A 7-layer columnar stack of such grains (as found in the discontinuous multilayers) has about 7×10^5 spins. Thus the measured moments may indicate correlated switching of a multi-grain complex. A columnar stack comprises only about 1/6000 of the area of one of our structures whereas a single switcher comprises about 1/80 of the total resistance change, further indicating that single grain switching is an unlikely candidate for the observed RTF's.

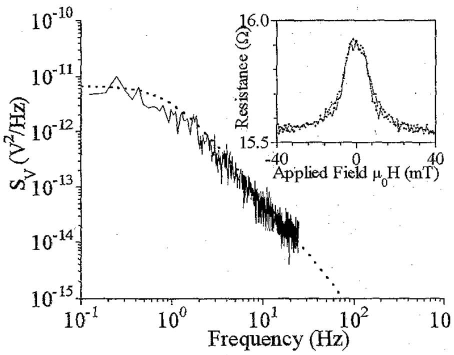

Fig. 1. Noise spectrum taken at T=108 K at an applied field of 4.04 mT. The superimposed Lorentzian curve is calculated from the up state lifetime, down state lifetime, and voltage difference. The inset shows a magnetoresistance (MR) curve for the 1.8 μm × 1.8 μm stripe.

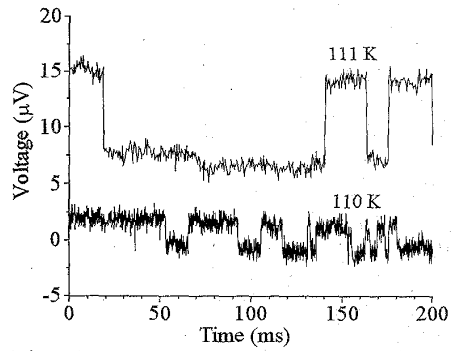

Fig. 2. Relative voltage as a function of time at an applied field of 6.24 mT. The time trace taken at T=111 K was taken 7 minutes after the time trace at T=110 K. Note the change in amplitude of the RTF.

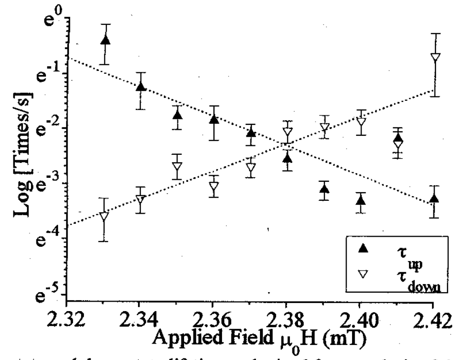

Fig. 3. Up state and down state lifetimes, obtained from analysis of the voltage time traces, plotted as a function of applied field at a temperature of 105 K. The error bars on the times are derived from statistical analysis of the exponential fit of actual measured times in the voltage time trace.

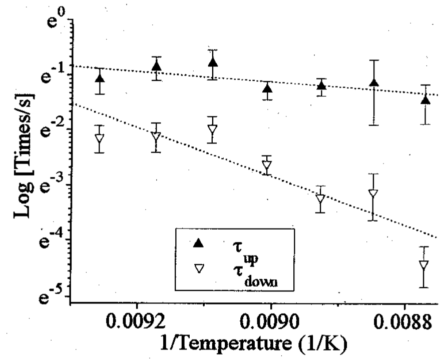

Fig. 4. Up and down state lifetimes plotted as a function of inverse temperature at an applied field of 4.02 mT. The linear fits through this data allows for calculation of activation energies and attempt frequencies for the two states. Note the much weaker dependence on temperature of the up state lifetime.

We stress that the model (1) for $1/\tau$ is a hypothesis and although μ is similar for different fluctuators, it is yet to be determined whether the differences between the field dependences of the up and down times can be thoroughly explained within this model. We theorize that the measured magnetic moments may be for a single grain or an effective moment for a cluster of grains that are switching coherently.

Temperature-dependent data at an applied field of 4.02 mT are shown in Fig. 4. Guided by (1), a semilogarithmic plot versus inverse temperature allows for linear fits. The slopes of these fits yield activation energies of 80.0 ± 36.6 meV and 378 ± 86 meV for the up and down time fits respectively. The intercepts of these linear fits yield prefactors of $7.65\times 10^{-5\pm1.7}$ s ($1.30 \times 10^{4\pm1.7}$ Hz) and $3.80 \times 10^{-19\pm3.9}$ s ($2.63 \times 10^{18\pm3.9}$ Hz) for up and down.

The fluctuator whose voltage time trace is illustrated in Fig. 2 from 111 K to 119 K gave similar activation energies and frequencies: 96.0 ± 54.9 meV and $5.88 \times 10^{4\pm2.4}$ Hz for the up state and 602 ± 83 meV and $2.92 \times 10^{27\pm3.7}$ Hz for the down state. These measurements indicate significant differences in the nature of the two levels.

We note that the apparently non-physical attempt frequencies of order 10^{22} Hz (for the down state) are a common observation for systems with temperature-dependent activation energies[6]. Certainly, we expect both μ and E_1 to go to zero by the Permalloy Curie point of ~700K. As an example, assuming a linear variation of E_1 with temperature, $E_1(T) = E_1(0)[1-T/T_{Curie}]$ and use the known value $T_{Curie} \approx 700$ K in (1), the characteristic frequency is modified by a factor of $\exp[E_1(0)/kT_{Curie}] \approx 10^3$.

Due to the difficulty of maintaining a single fluctuator under observation, we have not yet obtained both field and temperature dependent data on a single fluctuator. Although comparative data are not yet available, under the assumption that the domains whose activation energies were measured had magnetic moments on the order of 10^6 μ_B, the product of such magnetic moments with the field values at which they were active yields energies of the same order of magnitude as the measured activation energies. Ideally, we would like to know both the magnetic moments and activation energies over a broad range of both field and temperatures, and we hope that further work with smaller test structures will allow such studies.

Conclusion

We have observed resistance telegraph noise and its power spectral density in small $Ni_{82}Fe_{18}$/Ag discontinuous mutliayer structures. The resistance fluctuation amplitude and the decay rates for several different two-level fluctuators have been reported. These rates and amplitudes have enabled us to make qualitative estimates of the effective magnetic strengths, physical domain sizes, activation energies, and natural frequencies of several domains or clusters of grains. The moments we find seem reasonable and are roughly the same size for various fluctuators. We have observed both reversible, and irreversible changes in noise spectra. Finally, we point out that while the resistance noise is tolerable on the 1 μm scale, it will become severe in the sub-micrometer region, possibly affecting the usefulness of these materials for device applications.

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