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Fluctuation-dissipation relation for giant magnetoresistive $1/f$ noise

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We find that Co/Cu multilayers exhibiting giant magnetoresistance (GMR) also show giant magnetoresistive $1/f$ noise. The largest component of this noise (which peaks at magnetic fields maximizing the GMR derivative) is accurately predicted from a fluctuation-dissipation relation using the out-of-phase GMR in an ac field. A second noise mechanism, connected with defects in the antiferromagnetic order but not related to overall magnetization fluctuations, was found near zero field.

$1/f$ noise appears in the resistance of essentially all resistors.[1] There are plausible explanations for the noise in different materials, including various defect motions and magnetic fluctuations in metals.[1] It is unsatisfying, however, that even in cases where the origin of the resistor $1/f$ noise is well established, it has never been quantitatively shown to obey a fluctuation-dissipation (FD) relation.[2] Partly as a result, various exotic general theories of $1/f$ noise continue to flourish. The central obstacle to demonstrating a FD relation has been the lack of easily applied external fields which couple uniformly to the fluctuating variables.

In this paper we demonstrate a quantitative FD relation for $1/f$ noise in a resistor, exploiting the large, systematic coupling of the resistance to an external magnetic field provided by the giant magnetoresistance (GMR) effect[3] in Co/Cu multilayers. In addition, we use the FD relation to help distinguish between two distinct sources of GMR $1/f$ noise in these materials.

Co/Cu multilayers are among the best studied examples of transition-metal–nonmagnetic multilayer materials which exhibit the GMR effect.[4,5] In zero field the magnetic Co layers align ferromagnetically or antiferromagnetically, depending on the spacer layer thickness. Antiparallel (AP) antiferromagnetically aligned layers can be forced to align parallel (P) with an applied magnetic field, H. The GMR effect arises from the substantial difference between the resistances of the P and AP states.

To obtain the GMR effect the thickness of the Cu spacer layer is chosen to give AP alignment at $H=0$. In the absence of an external field the polarization axes are not fixed except by anisotropy effects, which are small in sputtered films. In a relatively small in-plane applied field the polarization axes should align nearly perpendicular to the applied field.[6] As the applied field is increased, the magnetization of the two sets of layers rotate more or less symmetrically (depending somewhat on anisotropy) toward the applied field, approaching a parallel alignment.

In these polycrystalline sputtered multilayers, R depends on the magnetic alignment, nearly following the very simple relationship.[7,8]

$$R = R_{\mathrm{AP}} - (M/M_S)^2 \Delta R \ . \tag{1}$$

Here M_S is the saturation magnetization, $\Delta R \equiv R_{\mathrm{AP}} - R_{\mathrm{P}}$, and R_{P} and R_{AP} are the parallel and antiparallel resistances, respectively. The spectral density $S_R(f)$ of the fluctuations in R is determined then by the spectral density $S_M(f)$ of the fluctuations in magnetization M along the field direction. $S_M(f)$ itself is given by a standard FD relation:

$$f S_M(f) = (2/\pi)\chi''(f) kT/V \ , \tag{2}$$

where $\chi''(f)$ is the out-of-phase magnetic susceptibility, k is Boltzmann's constant, T is temperature, and V is the sample volume. Then

$$\begin{aligned} f S_R(f) &= f S_M(f)(dR/dM)^2 \\ &= (8/\pi)\chi''(f)(M^2/M_S^4)(\Delta R)^2 kT/V \ . \end{aligned} \tag{3}$$

In order to express Eq. (3) in terms of resistive properties measurable on the same sample used for the noise measurement, we introduce a new quantity, $\chi_R''(f)$, which is the out-of-phase response of the resistance per unit of applied ac magnetic field. Experimentally, one obtains $\chi_R''(f)$ by measuring $R(t)$ (usually with an applied dc current) while applying an ac magnetic field with rms amplitude H_a, $2^{1/2} H_a \cos(2\pi f t)$. The resistance has a response $R(t) - \langle R \rangle = 2^{1/2} H_a \{\chi_R'(f)\cos(2\pi f t) + \chi_R''(f)\sin(2\pi f t)\}$.

If Eq. (1) holds,

$$\begin{aligned} |\chi_R''(f)| &= \chi''(f)|dR/dM| \\ &= 2\chi''(f)(\Delta R)|M|/M_S^2 \\ &= 2\chi''(f)\{\Delta R[R_{\mathrm{AP}} - R(H)]\}^{1/2}/M_S \ . \end{aligned} \tag{4}$$

Combining Eqs. (3) and (4), we find an expression for the standard dimensionless noise parameter $\alpha(f) \equiv f S_R(f) N/R^2$ [1], where N is the total number of atoms in the sample. (We avoid using the number of magnetic atoms, so that the expression can be directly applied to more complicated inhomogeneous materials.)

$$\alpha(f,H)=(4/\pi)(kT/\mu_S)|\chi''_R(f,H)| \times(\Delta R)^{1/2}[R_{AP}-R(H)]^{1/2}/R^2 . \quad (5)$$

Here $\mu_S = M_S V/N$ is the saturation moment per atom.

Equation (5) is particularly convenient because it expresses a resistance noise parameter in terms of the resistive response to a field. Thus artifacts in the magnetic response which are not connected with GMR (e.g., the alignment of an Fe underlayer) do not affect Eq. (5). Major deviations from Eq. (5) then indicate either some complication in the M-R relation [Eq. (1)] or some noise source not directly connected with magnetic moment fluctuations.

The samples discussed here, prepared at IBM, consist of 39 sputtered Co/Cu bilayers on a 50-Å layer of Fe on a glass subtrate. A top layer of Co covered with 30 Å of Zr is added. In both samples the Co layers are ~10 Å thick. Samples A and B have Cu spacer layer thicknesses of ~18 Å and ~9 Å, respectively. These thicknesses are near the first two antiferromagnetic peaks in the oscillatory interlayer coupling.[4] Both samples were photolithographically patterned into a bridge configuration with two parallel legs each 500 μm long and 3 μm wide. At room temperature we found GMR effects $\Delta R/R_P \approx 26\%$ in sample A and 45% in sample B as shown in Fig. 1.

$S_R(f)$ was found by applying a dc current to the bridge and measuring the random imbalance voltage. Typical spectra, with a $1/f$ form, are shown in Fig. 2. The excess of the voltage noise spectrum above background noise was quadratic in the dc current, indicating that the dc current simply probed quasiequilibrium resistance fluctuations.[1] However, using ac currents to measure R drastically altered the noise spectrum. The cause was presumably either the resulting inhomogeneous alternating magnetic fields of about 1 Oe or the periodic heating and cooling. Thus all the measurements shown here, both of $S_R(f)$ and of $\chi''_R(f)$ use dc probe currents. We emphasize that the relevant frequency in all that follows is that of the applied ac field, not the sample bias current.

The noise magnitude parameter α as a function of applied field H is shown in Fig. 3(a) for sample A. In order to facilitate taking a large number of accurate $\alpha(H)$ data points in a reasonable time, noise data from the range 29–41 Hz were used. Data at 2 Hz (the frequency of our χ''_R measurements) would have taken about an order of magnitude longer in time to collect, and would have been more susceptible to occasional low-frequency artifacts from drifts. As Fig. 2 illustrates, there is no problem at all in identifying α in the 35-Hz range with α(2 Hz).

The data shown in Fig. 3(a) were taken with H increasing from negative saturation. Data taken with H decreasing from positive saturation showed the opposite asymmetry. A large peak in α at fields near the maximum in $|dR/dH|$ is evident. Figure 3(b) shows noise data for sample B, in which another peak in α also occurs, near $H=0$.

We chose sample A for the FD comparison for two reasons: (1) It had much larger noise than sample B, making the measurement (particularly of χ''_R) much easier, and (2) sample (B) burned out before a similar measurement could be made on it. The $\chi''_R(f)$-vs-H measurement was made at 2 Hz to minimize phase errors, which became difficult to avoid at much higher f, while staying within the range of the lock-in amplifier. Within the narrow range of f explored (about a factor of 2), we found no sign of any f dependence of χ''_R. The ac field magnitude, H_a, was not important below 10 Oe. Our signal-to-noise became poor for $H_a < 1$ Oe.

A measurement of χ''_R(2 Hz) of sample A is shown in Fig. 4. The in-phase response χ'_R was determined to be 20 times larger than χ''_R. Due to hysteresis, χ'_R is about

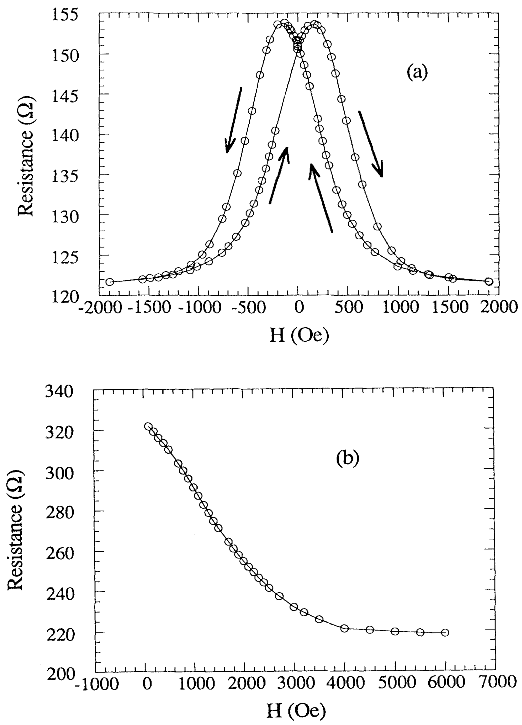

FIG. 1. The $R(H)$ curves at room temperature, with arrows indicating the direction of field sweep. (a) Sample A. (b) Sample B. The measuring currents, were close to 1 mA dc in these data and all data shown subsequently.

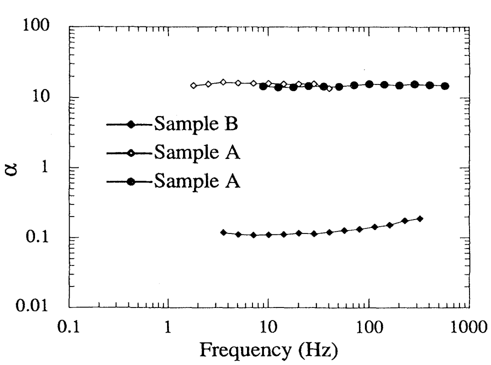

FIG. 2. Noise spectra [$\alpha(f)$], each taken at $H=400$ Oe. $1/f$ noise gives constant $\alpha(f)$. The two symbol types for sample A represent two runs taken over different frequency ranges.

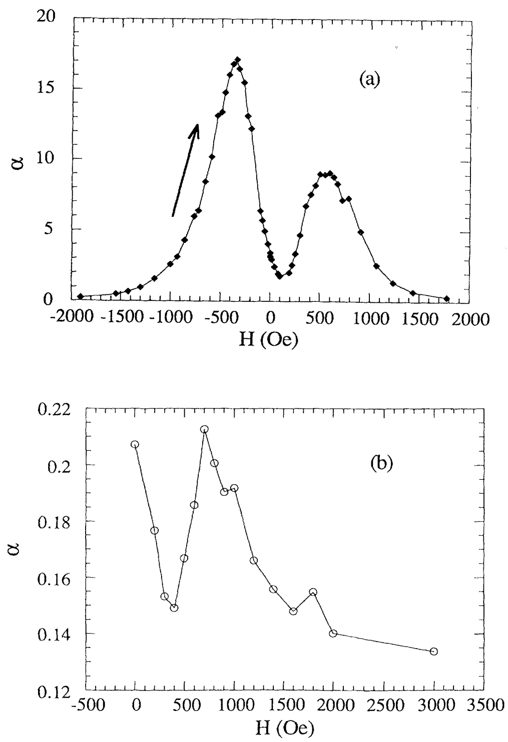

FIG. 3. $\alpha(H)$ for each sample. (a) Sample A, with both signs of H, and the direction of field sweep shown by the arrow. $f \approx 35$ Hz. (b) Sample B, with $H>0$, and results nearly independent of the direction of field sweep. $f \approx 160$ Hz.

60% of the slope of the $R(H)$ curve.

Figure 5 shows a comparison of the two sides of Eq. (5), as measured in sample A. (We assume that R_{AP} is identical to the maximum measured resistance, R_m.) *We emphasize that there are no adjustable parameters in this fit.* Except near $H=0$, the noise in sample A clearly is well described by Eq. (5). Even the field-history dependence of χ_R'' and α match well. Thus the magnetic structure is in quasiequilibrium despite the hysteresis effects. To the best of our knowledge this is the only case in

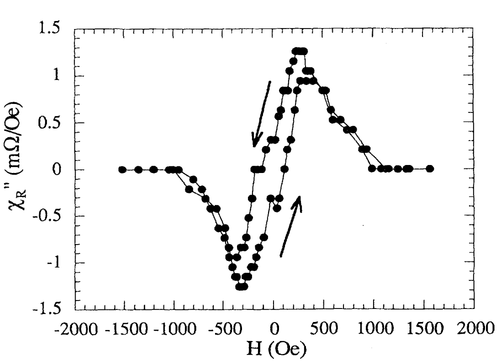

FIG. 4. $\chi_R''(2\text{ Hz}, H)$ for sample A, with the field sweep directions marked. The H_a used here was 9.55 Oe. The phase of the ac field was directly measured with a Hall sensor and the same amplifier chain used in the ac GMR measurement.

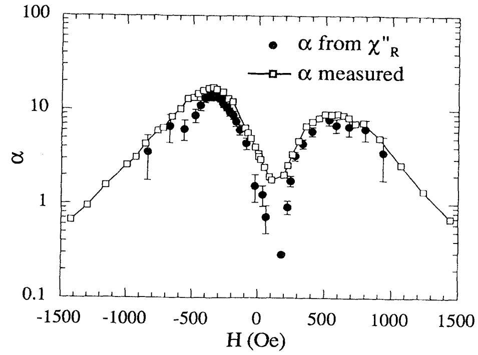

FIG. 5. The measured $\alpha(H)$ [Fig. 3(a)] is compared to that calculated via Eq. (5) from the χ_R'' data in Fig. 4.

which the magnitude of $1/f$ noise in a resistor has been accurately predicted by a FD argument.

Thus the noise results primarily from fluctuations in the P-vs-AP order, presumably caused by nearly degenerate metastable states produced by local domain-wall pinning and anisotropy. These same effects of course also account for χ_R'' and for the substantial hysteresis. An additional dramatic confirmation that the noise peak comes from fluctuations in the P-AP order was provided by observing large Barkhausen noise in R as the samples were driven from AP to P by sweeping H. We explore the implications of this Barkhausen noise for characterizing the domain sizes elsewhere.[9]

Close to $H=0$, however, the FD relation [Eq. (5)] breaks down, as shown in Fig. 5. The low-field noise is still far above the high-field background, so it is not from nonmagnetic effects. Defects in the AP structure can be present, so that using $R_{AP}=R_m$ in Eq. (5) may not be accurate. However, the factor $\chi_R''(H)$ in Eq. (5) necessarily passes through zero, so that even if we were to pick an adjustable $R_{AP}>R_{max}$ we could not make the low-field data fit Eq. (5).

In sample B there is also noise near $H=0$, with magnitude comparable to that found in sample A. Since sample B has much less noise than sample A in the main AP-P peak, it is useful for characterizing this low-field GMR noise.

We note first that the minimum in $\alpha(H)$ for sample B does *not* come from a shift of the $M \approx 0$ minimum due to field hysteresis. Sample B was exposed only to positive fields, so the $M=0$ point was actually shifted to $H<0$. Thus the peak in α near $H=0$ in sample B is a real effect, distinct from the pair of peaks which arise near the maxima in $|dR/dH|$.

The $H=0$ noise in sample B could be reduced by improving the antiferromagnetic order. Annealing the sample for 1 h at 400 K reproducibly decreased the noise by $\sim 30\%$, and increased R by $\sim 1\%$, indicating a clear association of the noise with defects in the AP order. Nonzero magnetizations at $H=0$ in similar samples show that such defects must in fact be present.[8] The effects of thermal annealing could be erased by field cycling through the P state.

Although it is easy to think of mechanisms by which defects in the AP order could make noise in R, it is not easy to think of such mechanisms that give sharply *decreasing* noise as H is increased enough to reduce the AP order but not to approach P saturation. For low fields the number of defects would be an increasing function of H.

One noise mechanism operative mainly at low H would be thermally activated rotation of domains with spontaneous resistive anisotropy.[10] At $H=0$ there is no overall preferred direction for M. Thus we would expect that rotations of anisotropic AP domains could give resistance fluctuations. This mechanism is quite independent of the net magnetic moment of the rotating domains, and thus need not couple to the external field. The effect is suppressed by fields too small to drive the domains parallel but sufficient to orient the AP domains perpendicular to the in-plane field. Defects may facilitate the rotations by breaking the AP order into small enough domains to have thermally activated rotations.

In conclusion, we have observed that the large resistive $1/f$ noise due to fluctuations between antiparallel and parallel alignment in Co/Cu multilayers nearly fits a simple FD prediction. This noise is largest when $|dR/dH|$ is large, i.e., near the operating point of a GMR field sensor. We have also found substantial $1/f$ noise at $H=0$, at least partly due to defects in the AP ordering. This low-field noise does not couple to the external field in the same way as the P-AP noise, and may instead involve rotations of the AP polarization axis. We also note, as a practical matter, that the $1/f$ noise in these GMR materials can be huge, which may give an unanticipated limit on their usefulness in some applications.

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