Low-Frequency Magnetic Noise in Micron-Scale Magnetic Tunnel Junctions

S. Ingvarsson and Gang Xiao
Physics Department, Brown University, Providence, Rhode Island 02912

S. S. P. Parkin
IBM Research Division, Almaden Research Center, Almaden, California 95120

W. J. Gallagher, G. Grinstein, and R. H. Koch
IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598
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We have observed low-frequency noise due to quasiequilibrium thermal magnetization fluctuations in micron-scale magnetic tunnel junctions (MTJs). This strongly field-dependent magnetic noise occurs within the magnetic hysteresis loops, either as $1/f$ or Lorentzian (random telegraph) noise. We attribute it to the thermally excited hopping of magnetic domain walls between pinning sites. Our results show that magnetic stability is a crucial factor in reducing the low-frequency noise in small MTJs.

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Magnetic tunnel junctions (MTJs) are good candidates for sensitive magnetic field sensors and magnetic random access memory devices. State-of-the-art optical lithography allows their production in large numbers at submicron length scales. In that size range, the dynamics of magnetization reversal are poorly understood theoretically. However, micromagnetic simulation is increasingly providing valuable insight and, in certain cases, good agreement with experiment [1].

In a magnetic tunneling system, many mechanisms can cause noise. Among these are Johnson-Nyquist noise, shot noise, $1/f$ resistance noise, and noise due to charge trapping in the oxide barrier. In a previous paper, we investigated electronic noise in MTJs [2]. Nowak *et al.* [3,4] have studied noise in MTJs with larger areas. The subject of this paper is the noise produced in MTJs by a very different mechanism: magnetic fluctuations. Although it is well known in principle that such fluctuations constitute an additional noise source in any magnetic system, low-frequency magnetic noise is usually hard to observe experimentally [5]. Owing to the strong coupling of junction resistance to magnetization in MTJs, however, it manifests itself clearly in our samples, thereby allowing the quantitative characterization of magnetic noise in these systems.

We report here the observation of field-dependent magnetization fluctuations in micron-scale MTJs. These fluctuations provide valuable information about the magnetic dynamics of these systems. In particular, they show that even very slow magnetization reversal occurs through a combination of smooth magnetization rotation and discontinuous jumps. They also show that magnetic instability, i.e., spontaneous, thermally activated jumps in magnetization, can be the dominant source of noise in small MTJs at low frequency. Furthermore, our results make clear that thermal magnetization fluctuations and disorder must be included in any micromagnetic simulations that hope to capture the details of magnetization reversal in small magnetic elements.

Our MTJ samples were fabricated by sputtering, and patterned using electron-beam (Type-A samples) and optical lithography (Type B and C) [6]. From transmission electron microscope (TEM) results we conclude that the grain size in our samples is typically 100–200 Å, and that the layer roughness is approximately 4–8 Å rms. All the samples have, on one side of the tunnel barrier, a layer of Co, exchange biased or "pinned" by an antiferromagnetic Mn-Fe layer. In the field range of our interest only the "free" layer of Ni-Fe on the opposite side of the tunnel barrier is allowed to switch its magnetization direction. A high (low) resistance state results whenever the magnetizations of the pinned and free layers are oriented antiparallel (parallel) to each other by the application of an external field.

An example of field-dependent magnetic noise is displayed in Fig. 1, for a Type-A sample. These data result from measurements of the junction resistance and resistance noise during a full cycle of the magnetic hysteresis loop. We stepped the magnetic field, H, slowly through the hysteresis loop, in ~1.5 Oe steps along the easy axis of the junctions. At each step, after allowing the sample to equilibrate for two minutes, we measured simultaneously the resistance $R(H)$ and the noise power spectrum, $S_R(f)$. As in all hysteretic systems, the results were influenced by sample history. If we measured the $R(H)$ loops ten times faster, e.g., or with different field sequences, then the size of the loops and the correlation between $R(H)$ and the noise was often noticeably different.

Figure 1(a) shows the $R(H)$ loop measured at dc, and its derivative dR/dH. The magnetization reverses abruptly at the switching fields allowing a direct comparison of the noise level in the two different magnetic states [parallel (P) vs antiparallel (AP)]. The asymmetry in the $R(H)$ loop could be a result of a 360° domain wall trapped within the

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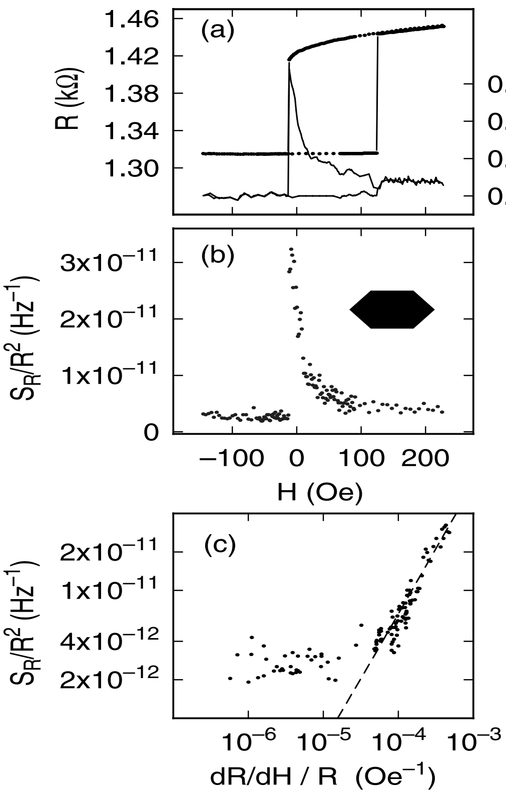

FIG. 1. Room temperature results for a Type-A sample with area $A = 0.45\ \mu\text{m}^2$. Resistance and noise spectra were measured simultaneously. (a) MR loop (dots) and its derivative (solid lines), dR/dH. (b) Noise at 100 Hz as field is ramped down from AP to P state. The inset shows the junction shape. (c) As the AP-P transition is approached the noise scales as the first power of dR/dH. The roughly horizontal part represents the resistance noise background. [Current bias = 10 μA (13–15 mV).]

sample in the AP state. Figure 1(b) displays the noise power spectral density as the field was ramped down (going from the AP to the P state). Over the entire frequency and field ranges of the experiment, the noise power spectra are $1/f$ in nature, and are notably sensitive to the magnetization state in the electrodes, thus implying that the noise is magnetic in origin. As the sample approaches the P state from the AP state, the noise increases substantially—by an order of magnitude—indicating the onset of strong magnetic fluctuations or instability. At switching, however, the noise drops precipitously, the P state being much quieter magnetically than the AP state. In the vicinity of the P → AP transition (not shown in Fig. 1), moreover, there is little hint of instability, the noise being flat on both sides of the transition, with a vertical step at the switching field. Outside the hysteresis region, the saturation value of the noise in the AP state exceeds that of the P state by a factor of 2.

The most striking feature of the data is the similarity between the noise in Fig. 1(b) and the slope dR/dH in Fig. 1(a). Figure 1(c) shows that, within the unstable region close to the AP → P transition, the noise scales as dR/dH to the first power.

While magnetic-field-dependent $1/f$ noise occurs within the hysteresis loops of many of our samples, other samples exhibit field-independent $1/f$ noise, except within one or a few narrow field ranges. Figure 2 shows one such example (Type B), where the left panels display $R(H)$ and S_R/R^2 measured simultaneously as the field is swept from −50 to 110 G (i.e., from the P state to the AP state). The $R(H)$ loop consists of straight horizontal regions, with essentially zero susceptibility, and discrete steps that presumably stem from domain wall pinning at the sample's edges. Unlike the Type-A sample, there is neither a change in noise near the P → AP or AP → P transitions nor any difference in the noise power of the saturated states. Within a narrow field range inside the hysteresis loop, however, there appears a reproducible, large-amplitude noise peak that occurs only in the P state, and exceeds the background noise by 1 order of magnitude. $R(H)$ remains constant through this noise peak, indicating a very small change in the net magnetization associated with it. (In other samples, peaks appear in the hysteresis region in the AP rather than the P state; peaks can also be present in both states.)

The right-hand panels in Fig. 2 show the power spectra at successive fields labeled as a to e within the noise peak in the bottom left panel. Outside the peak, the spectra

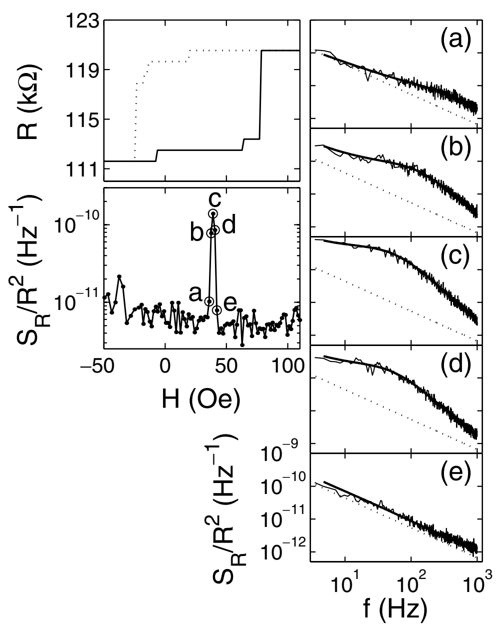

FIG. 2. Left panels: magnetoresistance loop, $R(H)$, and normalized noise power spectral density S_R/R^2 as a function of magnetic field at room temperature. Right panels: noise spectra measured near the noise peak region (a, b, c, d, e). The solid lines show a nonlinear Levenberg-Marquardt fit, with a Lorentzian and $1/f$ function. The dotted lines represent the $1/f$ dependence outside the peak. [Type-B sample with a rectangular free electrode $1 \times 2\ \mu\text{m}^2$, current bias = 1.12 μA (125–135 mV).]

indicate pure $1/f$ noise. Near the feet of the peak (*a* and *e*), the spectra show faint signs of Lorentzian character. However, in the peak region (b, c, d), the spectra have strong Lorentzian character, suggesting that the noise comes mostly from a single, effective two-level fluctuator. As the external magnetic field moves through the noise peak, the Lorentzians change in a predictable way, consistent with a change from one of the levels being energetically favorable to the other [7].

Figure 3 shows the magnetoresistance (MR) loops and resistance noise from a sample of Type *C* that exhibits *both* magnetic $1/f$ and Lorentzian noise, the latter occurring within the peaks in the figure, and the former occurring between peaks. At $T = 4.2$ K, the power spectra in the peaks behave like $1/f^2$, which we interpret as a Lorentzian with a roll-off frequency lower than our experimental cutoff of 1 Hz. At higher temperature, typical roll-off frequencies are higher, reaching ~100 Hz at room temperature. This presumably reflects the higher transition rates of the effective two-level systems involved. Higher temperature is also accompanied by larger amplitude of the $1/f$ noise within the hysteretic part of the MR loop.

What is the origin of the observed noise? Magnetic domain fluctuations in the free electrode are one obvious candidate. Magnetic impurities inside the barrier are also potential contributors, as are spin-dependent charge traps. To identify the source, we first analyzed the Lorentzian noise near one of the peaks of a Type-*C* sample. The presence of this peak in the P state and its absence in the AP state rule out magnetic impurities in the barrier. Also, the total transition rate of the effective two-level system responsible for the Lorentzian noise within the peak was found to be completely independent of applied bias [8]. Consequently, neither spin-dependent traps nor current-induced magnetic fields can be responsible for the noise [9,10]. Owing to surface tension, moreover, the vibrational excitations of domain walls result in high-frequency noise. Thus, within our low-frequency range, the Lorentzian noise must be due to thermally activated domain wall hopping between pinning sites. The pinning sites could be produced by, e.g., surface or edge roughness, bulk defects, or disorder in the film (such as random anisotropy).

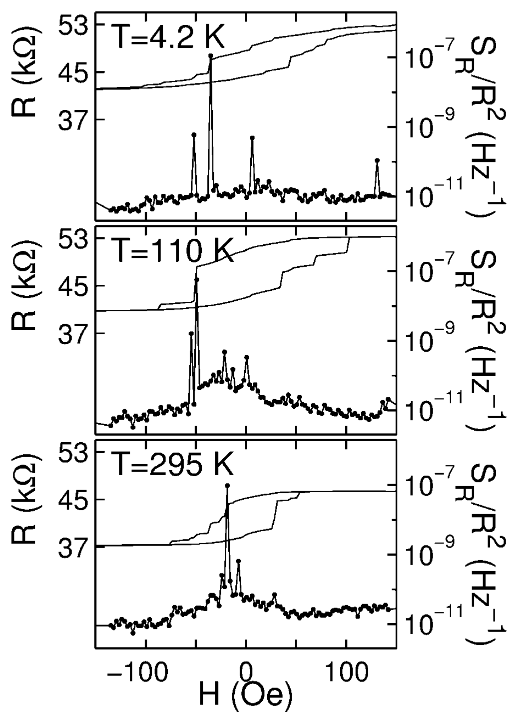

FIG. 3. Temperature dependence of the noise from a rectangular 1×3 μm^2 sample of Type *C*. At low temperature the magnetic noise appears mostly as Lorentzian noise within narrow peaks; as the temperature is raised, the $1/f$ noise within the hysteretic part of the MR loop increases and roll-off frequencies of the Lorentzian noise increase. Field is ramped from the AP to P state. [Current bias = 1.1 μA (40–59 mV).]

We have estimated the magnetic moment of the effective two-level system responsible for the large peak in Fig. 2. The transition rates were assumed to follow [11]

$$\frac{1}{\tau_{i-j}(\mathbf{H})} = \frac{1}{\tau_0} \exp\left(-\frac{E \pm \Delta\mathbf{m} \cdot \mathbf{H}}{kT}\right), \qquad (1)$$

where τ_{i-j}^{-1} is the transition rate from state i to state j and τ_0^{-1} is an attempt frequency; E is the field-independent activation energy, and $\Delta\mathbf{m} \cdot \mathbf{H}$ is a Zeeman term for the fluctuating magnetic moment $\Delta\mathbf{m}$. Then $\tau_{1-2}(\mathbf{H})/\tau_{2-1}(\mathbf{H}) \propto \exp(2\Delta\mathbf{m} \cdot \mathbf{H}/kT)$. A fit to our data results in $\Delta\mathbf{m} \sim 4 \times 10^6 \mu_B$, where μ_B is the Bohr magneton. This corresponds to an area ΔA of about 4×10^{-3} μm^2 in the free electrode, whose total area is $A = 2$ μm^2. This small fraction of the total area accounts for the apparent constancy of the magnetization, and hence of the resistance, as the field is swept through the noise peak.

In view of the Dutta-Dimon-Horn model [12], our results suggest that the observed magnetic $1/f$ noise results from the superposition of spectra from effective two-level systems with a broad distribution of activation energies, formed by domain wall hopping between pinning sites.

In order to understand the correlation between this noise and dR/dH shown in Fig. 1(c), we use the following familiar form of the Kramers-Kronig relation, expressing the dc value of the susceptibility as an integral over all frequencies of the imaginary part of the susceptibility [13],

$$\chi'(f = 0) = \frac{2}{\pi} \int_0^\infty \frac{\chi''(f)}{f}\, df\,. \qquad (2)$$

Our samples are hysteretic, and so do not exhibit linear response for small fields. As such, they are not in thermal equilibrium. Therefore, there is no *a priori* reason why the fluctuation-dissipation theorem should apply. Indeed there are cases where it has been shown to hold in the saturation region of a ferromagnetic system, but to fail within the hysteresis loop [14]. However, the fact that we see $1/f$ noise suggests that, at each field value inside (i.e., on a given branch of) the hysteresis loop, our samples may achieve approximate ("quasi") thermal equilibrium in the restricted subset of states accessible on the time scales over which the measurements are performed. If this is so, then one might expect the fluctuation-dissipation theorem to continue to hold, at least roughly. The theorem (in SI units) takes the form,

$$S_m = \frac{2k_B T}{\pi \mu_0 f} \chi_m'' , \tag{3}$$

where m is the total magnetic moment of the sample, μ_0 is the vacuum permeability, and S_m and χ_m'' are the magnetic noise and the imaginary part of the magnetic susceptibility, respectively. Together with (2), and the relations $S_R = (\frac{\partial R}{\partial m})^2 S_m$ and $\frac{\partial m}{\partial H} = \frac{\partial m}{\partial R}\frac{\partial R}{\partial H}$, this leads to

$$\left.\frac{\partial R}{\partial H}\right|_{f=0} = \frac{2\mu_0 m}{k_B T \Delta R} \int_0^\infty S_R(f)\, df . \tag{4}$$

Here we have used $\frac{\partial m}{\partial R} \sim \frac{2m}{\Delta R}$, where $2m$ and ΔR are the respective changes in magnetic moment and resistance under magnetization reversal of the free layer. Note that the validity of Eq. (4) rests solely on the system achieving quasiequilibrium, and is largely independent of the detailed microstructure.

Now suppose that over a sizeable range of f, $f_{\min} < f < f_{\max}$, say, $S_R(f)$ has an algebraic dependence: $S_R = \tilde{S}_R / f^\gamma$ for some coefficient $\tilde{S}_R$ and exponent γ. Then the integral in Eq. (4) is simply proportional to $\tilde{S}_R$. It then follows from (4) that, if $f_{\max}$ and $f_{\min}$ depend only weakly on field, the dc value of dR/dH should be proportional to the noise at any fixed frequency, the proportionality constant being essentially independent of field. If the power γ is close to unity, which is indeed the case in our data, where $\gamma \sim 0.95$, then the proportionality constant depends only weakly (logarithmically in the limit of strict $1/f$ noise) on $f_{\min}$ and $f_{\max}$, so one can estimate it quite well from Eq. (4). The measured values of the noise and of the dc dR/dH then provide a quantitative test of the validity of the fluctuation-dissipation theorem, and hence of the hypothesis of quasiequilibrium.

We have performed this test on data from the sample discussed in Fig. 1. This sample has noise very close to $1/f$ (viz., $\gamma \sim 0.95$), over our experimental frequency range of 1 Hz to 1 kHz. The data for dR/dH at zero frequency as a function of field indeed track those for S_R at arbitrary fixed frequency [Fig. 1(c) shows the results at $f = 100$ Hz]. The proportionality constant is close to that predicted by Eq. (4), provided we take $f_{\max}/f_{\min} \sim 10^9$ Hz, i.e., make the reasonable assumption that the $1/f$ noise persists over nine decades. Different choices for this range produce less precise, though still fairly good, agreement. It should be emphasized that Eq. (4) holds for *magnetic* noise, irrespective of external field direction or magnitude. Application of a hard axis field component to our samples reduces their hysteresis loops. However, this also suppresses the maximum susceptibility, thus limiting the magnetic noise in the sample, according to Eq. (4). When the susceptibility (dR/dH) is very low [e.g., lower branch in Fig. 1(a)], magnetic noise is no longer predominant, and S_R/R^2 in Figs. 1(b) and 1(c) is dominated by field-independent resistance noise.

In summary, we have reported observations of low-frequency magnetic noise in ferromagnetic tunnel junctions. These measurements are facilitated by the linear relation between the conductance and the magnetization. The noise is either $1/f$ or Lorentzian in character. It is produced neither by spin-dependent potential trapping nor magnetic impurities in the tunnel barrier, but by thermally excited hopping of domain walls between pinning sites. When the noise is $1/f$, it is consistent with the fluctuation-dissipation theorem, suggesting that the system achieves quasiequilibrium on a given branch of the hysteresis loop. In this case, the noise tracks the dc susceptibility. Our results indicate that, to curtail the low-frequency noise in MTJs, one must enhance the thermal stability of the magnetization by reducing the activated motion of domain walls and the associated susceptibility.

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