

Low-frequency magnetic and resistance noise in magnetic tunnel junctions

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We have studied the voltage fluctuations of current-biased, micron-scale magnetic tunnel junctions. We find that the spectral power density is $1/f$ -like at low frequencies and becomes frequency independent at high frequencies. The frequency-independent background noise is due to Johnson-Nyquist noise and shot noise mechanisms. The nature of the $1/f$ noise has its origin in two different mechanisms. In the magnetic hysteresis loops this noise power is strongly field-dependent and is due to thermal magnetization fluctuations in both the “free” and “fixed” magnetic layers. We attribute these magnetic fluctuations to thermally excited hopping of magnetic domain walls between pinning sites. At high temperatures, this magnetic noise is found to track the dc resistance susceptibility but it is not in quantitative agreement with the fluctuation dissipation relation, indicating that the magnetic structure is not in equilibrium. A second mechanism for the $1/f$ noise, connected with defects in the tunnel barrier but not related to the overall magnetization fluctuations, was found at fields for which the magnetic structure in the free and fixed layers is well aligned. We attribute this noise to electron trapping processes having thermally activated kinetics and a broad distribution of activation energies. Below ~ 25 K the noise power is temperature independent suggesting that the kinetics are dominated by tunneling. Our results show that the thermal stability of both the magnetic layers and the quality of the tunnel barrier are important factors in reducing the low-frequency noise in magnetic tunnel junctions.

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INTRODUCTION

Major advances in our understanding and ability to fabricate multilayered thin film structures of ferromagnetic layers separated by thin nonmagnetic layers have led to important applications of these materials.¹ These applications exploit spin polarized electronic transport that occurs in these structures and can lead to very large changes in resistance when they are subject to magnetic fields.² In particular, magnetic tunnel junctions (MTJ's) are the focus of intense interest for magnetic field sensing and magnetic random access memory applications.³ In these structures two ferromagnetic layers are separated by a thin, nonconducting layer. The resistance as measured perpendicular to the layers depends on the relative orientation of the magnetization of the two magnetic layers. Recent developments in materials deposition, processing, and lithographic techniques have led to submicron sized junctions exhibiting magnetoresistance (MR) ratios in excess of 40% and low resistance-area products.^{4,5}

Despite this progress, a better understanding of the barrier material and the interfaces and the dynamics of the magnetization reversal are necessary to have a realistic picture of spin-polarized conduction in these systems. Structure, chemistry, and magnetism are important factors that also affect the noise that is observed in MTJ's. For technological prospects, the sensitivity of devices based on MTJ's will be limited by their intrinsic noise. Characterizing the intrinsic noise and identifying its origin is then particularly relevant to making MTJ's with optimal properties for information storage and field sensing applications. In this paper we use noise to probe the electronic and magnetic properties of MTJ's.

In a tunneling system, the main mechanisms that cause

electrical noise are Johnson-Nyquist noise, shot noise, and noise due to charge trapping in the oxide barrier.⁶ $1/f$ resistance noise in the metal electrodes is another source of noise that may be important in low resistance junctions. In magnetic tunneling systems, thermal magnetization fluctuations can couple to the resistance through the spin-dependent tunneling effect and create resistance noise. When the various mechanisms can be distinguished (e.g., either by the spectral properties, field dependence, etc.) then the noise provides valuable information about the defects in the tunnel barrier and the magnetic dynamics of these systems.

In previous work we investigated low-frequency voltage fluctuations in MTJ's.⁷⁻⁹ These fluctuations were due to Johnson, shot, and $1/f$ noise mechanisms. The $1/f$ noise was attributed to trapping processes and was found to depend sensitively on the relative position of the oxide edge and the nature of the ferromagnet-Al interface.^{8,9} In that work and in other studies,^{10,11} the $1/f$ noise did not show any noticeable dependence on magnetic field for a given alignment of the two electrodes. In some MTJ's the $1/f$ noise provided evidence of bias-dependent current-path rearrangements, indicating that an inhomogeneous (filamentary-like) current-flow pattern existed across the tunnel junction.⁷ Voltage-bias dependent noise was also observed by Ingvarsson *et al.*¹⁰ and attributed to charge traps in the barrier. In addition, they found that submicron scale MTJ's exhibited both $1/f$ and Lorentzian noise that was magnetic in origin. This noise was associated with reversible domain switching or domain wall jumps in the magnetically soft layer.¹² Magnetic field dependent noise has been also observed in larger area junctions by Kim *et al.*¹³

We report here measurements of low-frequency voltage

fluctuations as a function of magnetic field and temperature in relatively large and submicron scale MTJ's. The power spectrum of the noise can be frequency independent, $1/f$ -like, or Lorentzian in character. The noise has its origin in thermal, shot, charge trapping, and magnetic mechanisms. Strong increases in noise power are found near magnetic fields at which the magnetically free and fixed layers undergo reversal; i.e., where the dc susceptibility peaks in the magnetic hysteresis loops. These results show that spontaneous thermally activated jumps in magnetization in both the free and fixed magnetic layers can be the dominant source of noise in MTJ's. This magnetic noise is superimposed on a field-independent $1/f$ resistance noise background that is due to charge trapping in the oxide tunnel barrier.

EXPERIMENT AND RESULTS

The MTJ material stack was grown by magnetron sputtering onto SiO_2 -coated Si wafers.⁵ The stack includes two magnetic layers separated by an Al_2O_3 barrier and additional layers that serve to pin the polarization of one of the magnetic layers in a fixed direction. The fixed layer is part of a synthetic antiferromagnet (SAF) pinned by an IrMn antiferromagnetic layer beneath it, the entire structure being IrMn/pinned layer/Ru/fixed layer/ AlO_x /free layer. We report results on junctions having two different types of SAF's: type *A* is NiFe(27 Å)/Ru(7 Å)/NiFe(17 Å)/CoFe(5 Å) and type *B* is CoFe(23 Å)/Ru(7 Å)/CoFe(23 Å). The relatively low saturation field of the type-*A* SAF (< 1000 Oe) makes it possible to evaluate noise related to rotation of the fixed layer moment with moderate applied fields. The free layer is a 40 Å thick film of NiFeCo. The tunnel barrier is made from a ~ 9 Å thick layer of Al metal that is plasma oxidized. The resistance of the tunnel junction is either low or high depending on the relative magnetization, parallel (P) or antiparallel (AP), of the free layer with respect to the fixed layer.

After deposition the wafers were annealed at 250 °C to improve the tunnel barrier. Standard lithographic techniques were then used to pattern the materials stack down to submicron dimensions and to form interconnects that allow current to be passed perpendicular to the tunnel junction. The wafer was then diced and gold wire bonding was used to attach two leads to the bottom and top of the stack, i.e., a 2-probe measurement. The nominal resistance-area (RA) product of these MTJ's was $6 \text{ k}\Omega \mu\text{m}^2$ of which the contact resistance was estimated to contribute roughly $0.04 \text{ k}\Omega \mu\text{m}^2$ for type-*A* junctions and $0.23 \text{ k}\Omega \mu\text{m}^2$ for type-*B* junctions. We report noise properties on MTJ's having free layers that are in both rectangular and ellipselike shapes (aspect ratios ≤ 3) with areas that vary from $0.4 \mu\text{m}^2$ to $100 \mu\text{m}^2$.

An example of a typical MR curve is shown in Fig. 1. At room temperature the MR is $\sim 33\%$, defined as $\Delta R/R_P$ where ΔR is the change in resistance and R_P is the resistance in the P state. For these MTJ's, the free layer has a coercive field less than ~ 50 Oe and the hysteresis loop is quite square. To flip the orientation of the fixed layer requires several hundred oersteds, depending on the type of SAF. The magnetic reorientation is also much more gradual, occurring over ~ 400 Oe.

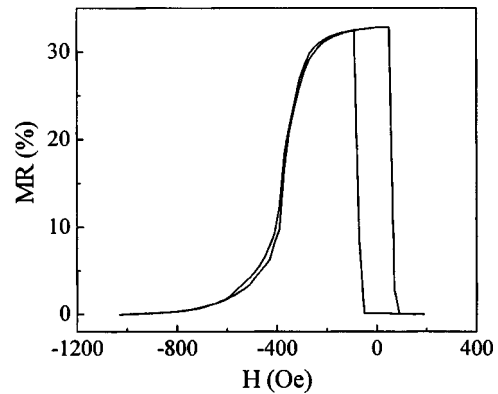


FIG. 1. Room temperature magnetoresistance of a type-*A* junction having area $A = 0.51 \mu\text{m}^2$. The average bias voltage across the junction was 200 mV.

Figure 2 shows the bias dependence of the differential resistance and the MR measured at $T = 300$ K. Because the magnetic electrodes are made of two different metals, it is reasonable to expect a mismatch in the density of electronic states for tunneling across the insulating barrier, regardless of the magnetic orientation of the layers. This leads to asymmetric current-voltage characteristics. Such pronounced asymmetries are not seen for MTJ's having identical electrodes.⁸ The MR peaks at 40%, at a dc bias of 25 mV. It drops to half of its peak value at about 300 mV. At $T = 2$ K, both the tunneling resistance and MR are approximately 10% larger.

Voltage noise measurements were performed under constant current conditions by using a battery and a ballast resistor. Two-probe measurements can be sensitive to contact noise. However, studies of junctions with low resistance tunnel barriers, due to dielectric breakdown, showed noise levels a factor of 100 smaller than before the dielectric breakdown occurred, confirming that contact noise was negligible. The power spectral density of the noise was studied as a function of current, temperature, and magnetic field.

Figure 3 shows an example of a power spectrum of the voltage noise. The spectrum is comprised of a broadband

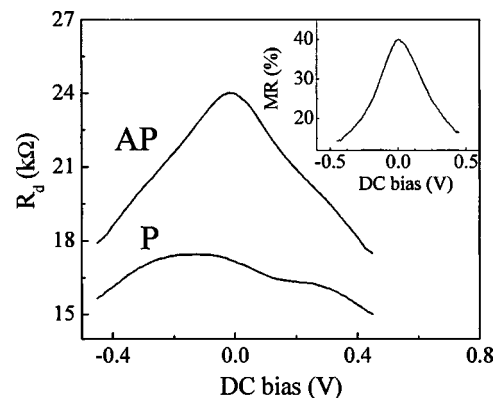


FIG. 2. The differential resistance, $R_d = dV/dI$, is plotted as a function of the bias voltage across the junction. The inset shows the characteristic decrease of the MR with bias. Data was taken at $T = 300$ K on a type-*B* junction.

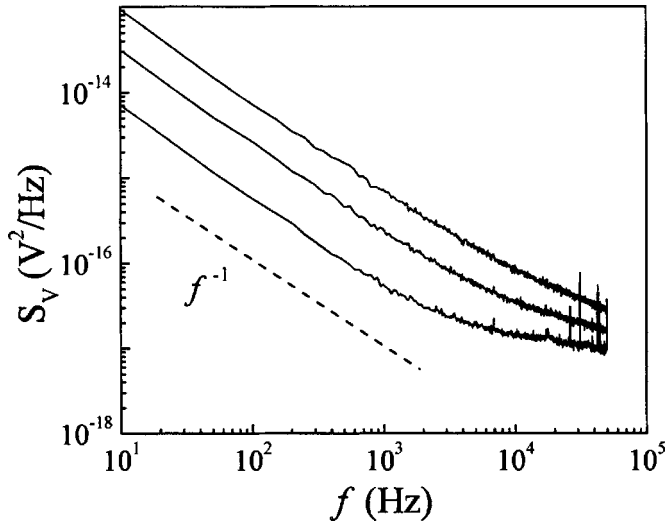


FIG. 3. The power spectral density of the voltage fluctuations shows a crossover from $1/f$ noise at low frequency to frequency independent shot noise at higher frequency. Spectra were measured on a type-A junction at $T=2$ K for different dc currents: $I=0.36$, 0.73 , and 1.28 mA, from bottom to top. The dashed line is a guide to the eye.

$1/f$ -like component at low frequencies superimposed on a frequency independent component. The frequency independent component, or “white” noise, has its origin in thermal and shot noise mechanisms. It has been shown that conventional¹⁴ and magnetic⁸ tunnel junctions exhibit thermal and shot noise given by the expression

$$S_V = 2eIR_d^2 \coth\left(\frac{eV}{2k_B T}\right), \quad (1)$$

where e is the charge of the electron, I is the dc current, V is the dc bias voltage across the tunnel junction, R_d is the differential resistance (dV/dI), and k_B is Boltzmann’s constant. At low T and high voltage biases, $eV \gg k_B T$ and the expression reduces to the familiar shot noise relation, $2eIR_d^2$. Shot noise is most evident at low T as shown in Fig. 4 where it can be seen that the noise power is in good quantitative

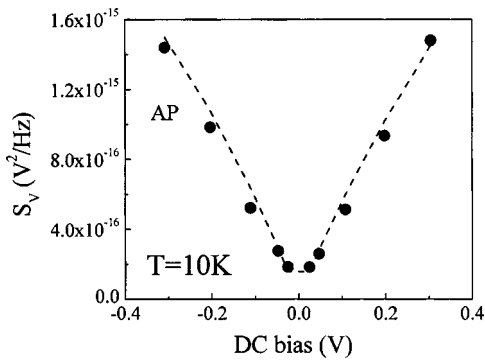


FIG. 4. The magnitude of the frequency independent portion of S_V is plotted as a function of the bias voltage across the junction. Data is shown for $T=10$ K for the AP state of a type-B junction. S_V scales in agreement with the predicted shot noise [see Eq. (1)], which is depicted by the dashed line.

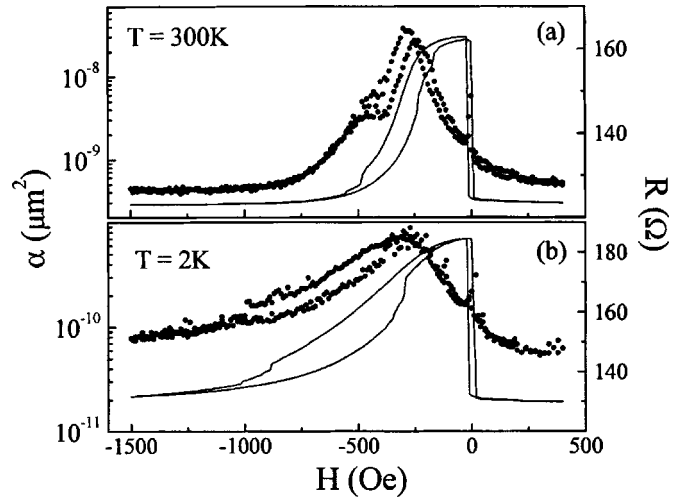


FIG. 5. The magneto-resistance loop, $R(H)$, and normalized noise, α , at 45 Hz are plotted as a function of magnetic field. Resistance (solid line) and noise (dots) were measured simultaneously as the field was ramped from 400 Oe to -1500 Oe and back to 400 Oe. The noise is found to be largest when the free and fixed magnetic layers are undergoing reversal. (Current bias = 1.25 mA, type-A junction, $A = 48 \mu\text{m}^2$.)

agreement with Eq. (1). At a fixed voltage bias, the noise smoothly crosses over from shot to thermal noise as the temperature increases. At room temperature and for typical biases (~ 100 mV) the noise is largely thermal in nature.

The crossover between $1/f$ -like and white noise is bias dependent but typically occurs at a few kHz for good quality junctions. Here, as in previous work,^{7,8,12} the $1/f$ noise power scales approximately with the square of the current, consistent with resistance fluctuations. We parameterize the magnitude of the $1/f$ noise power by a normalized noise parameter, $\alpha = \Omega f S_V / I^2 R_d^2$, where Ω is the volume of the sample.¹⁵ In MTJ’s, we replace Ω by A , the cross-section area of the MTJ, and thereby incorporate any effects due to its thickness into the parameter α . The total noise power spectral density is then given by

$$S_V \approx 2eIR_d^2 \coth\left(\frac{eV}{2k_B T}\right) + \frac{\alpha I^2 R_d^2}{Af}. \quad (2)$$

The nature of the $1/f$ noise in these micron-sized MTJ’s can be categorized by two components: a magnetic field-independent part and a field-dependent part. Measurements of the junction $1/f$ noise were done during a full cycle of the magnetic hysteresis loop. The magnetic field was applied along the easy axis of the magnetic electrodes and stepped slowly through the hysteresis loop, in ~ 10 Oe steps. At each step and after a period of sample equilibration, the resistance, $R(H)$, and noise power spectrum were measured simultaneously.

Figure 5 shows the dc resistance and α as the field was ramped from $+400$ to -1500 and back to $+400$ Oe. α is notably sensitive to the magnetization state of the electrodes, thus implying that the noise is, in part, magnetic in origin. Substantial increases in noise are observed at magnetic fields

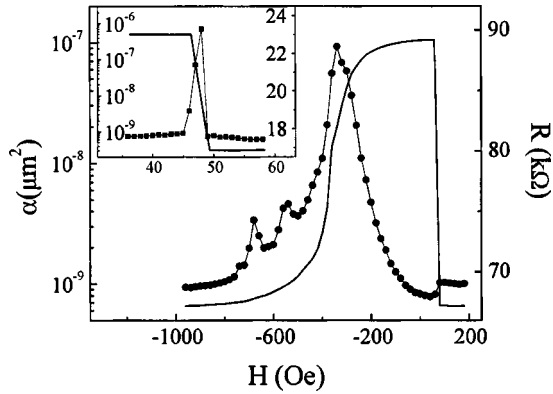


FIG. 6. Additional examples of $R(H)$ (solid lines) and $\alpha(H)$ (dots) for two different junctions with $A = 0.5 \mu\text{m}^2$. Data is taken at room temperature as the field was ramped along one branch of the magnetic hysteresis loop. $\alpha(H)$ is nearly field independent when the magnetic layers are well aligned in the P or AP states. The inset also shows a dramatic spike in noise when the free layer undergoes reversal. Lorentzian spectra are observed at fields near this spike. The axes in the inset have the same units as those in the main panel. (Main panel: type-A junction; inset: type-B junction.)

at which either the free or fixed magnetic layer is undergoing a reversal. At low fields where the free layer switches orientation abruptly, the noise power can be a factor of 10^3 larger; see inset of Fig. 6. Because the samples are hysteretic, the results were influenced by sample history. If the measurements were done with different field sequences then the correlation between the measured $R(H)$ loops and the noise was somewhat different.

A striking feature of the data is the similarity between the noise and the slope dR/dH shown in Fig. 7. Both α and dR/dH show peaks at nearly the same fields. The largest and narrowest spikes in noise power are associated with the re-

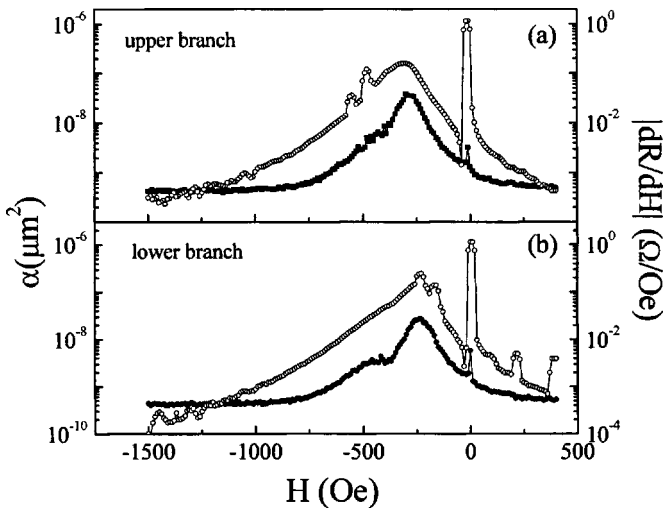


FIG. 7. Plotted is the field dependence of the noise (solid dots) and the absolute value of the derivative of $R(H)$ (open dots) for the same data shown in Fig. 5. The data was taken at $T = 300$ K for both branches of the hysteresis loop. The noise and dR/dH are observed to have similar field dependences. The large, broad peak and the narrow peak occur at nearly the same field for both quantities.

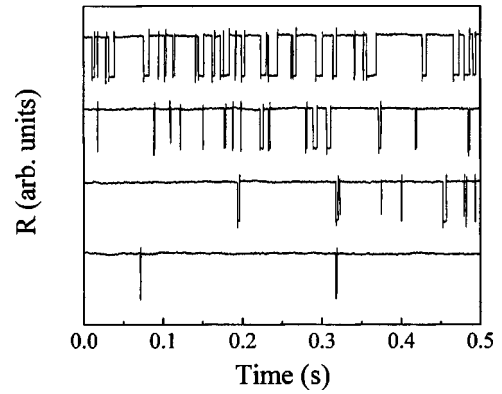


FIG. 8. Telegraph noise is often found at fields for which the free magnetic layer is undergoing a reversal in orientation. Shown is the field dependence on the telegraph noise for fields corresponding to the AP \rightarrow P transition: $H = 47.35, 47.54, 47.75,$ and 47.95 Oe (from bottom to top). The extreme sensitivity of the signal's duty cycle on applied magnetic field is evident. Data is for a type-B junction having $A = 0.5 \mu\text{m}^2$.

versal of the free layer, e.g., Fig. 6 inset. (The spike is smaller in Fig. 5 and is absent in the main panel of Fig. 6 due to undersampling, i.e., the magnetic field steps are large.) Coincident with these spikes we often find strong deviations from a $1/f$ -like frequency dependence. These deviations appear as a Lorentzian spectrum. Analysis of the voltage versus time traces of the noise at fields within the transition region reveals random switching between two distinct voltage levels or states, i.e., random telegraph noise. An example of the telegraph noise is displayed in Fig. 8 for a sample undergoing a AP \rightarrow P transition. The fractional change in resistance associated with the telegraph signal is large, $\sim 0.08\%$. Equally remarkable is the strong dependence of the signal's duty cycle on magnetic field. The characteristic lifetimes in the high resistance state can vary from nearly zero to 100% in the span of less than 1 Oe.

In general, the occurrence of a *specific* fluctuator at a particular field is not reproducible, but rather it is found to depend on the sample's magnetic history. Too large a change in field causes the fluctuator to disappear, typically remaining unrecoverable. Telegraph noise can be found for both the P \rightarrow AP and AP \rightarrow P transitions but differs in details, such as range of fields, size of fluctuator, and characteristic switching times. This is made more evident in a different set of MTJ's that showed broader, multi-domain-like behavior for the $R(H)$ loops. An example is displayed in Fig. 9 where we plot the two branches of a $R(H)$ loop and the corresponding $\alpha(H)$. For this range of fields only the free layer is undergoing reversal. Near a transition $\alpha(H)$ can be described as having a complex sequence of large, narrow spikes riding on top of a smaller broader peak. The fine structure in $\alpha(H)$ differs for the P \rightarrow AP and AP \rightarrow P transitions. In some cases, spikes in α that occur at a given H in the P state is absent for the same H in the AP state. The power spectrum at any given H is best described as a superposition of one or more Lorentzians on a $1/f$ background. Pronounced deviations from a $1/f$ form are found at the

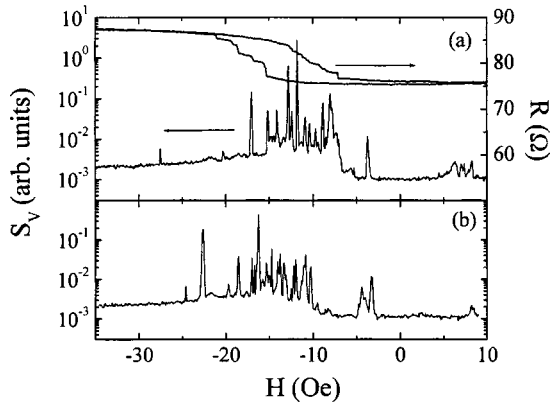


FIG. 9. $R(H)$ and noise measured at room temperature as the applied field was ramped from +20 to -40 and back to +20 Oe in ~ 0.1 Oe steps. Data is from a MTJ ($A = 100 \mu\text{m}^2$) that is made from a different materials stack that exhibits a broad magnetic hysteresis loop. $S_V(H)$ is shown for the upper branch of the hysteresis loop in (a) and for the lower branch in (b).

spikes; for some of the larger spikes telegraph noise is apparent in our bandwidth.

When the fixed layer is in the process of reversal the noise power also peaks but its spectrum is featureless $1/f$ noise. That is, Lorentzian spectra were not observed, although with finer field resolution they may be apparent where the susceptibility spikes.

Outside these transition regions where the magnetic state is P or AP, both the resistance and noise have negligible dependence on magnetic field. This behavior is highlighted in Fig. 6. It is generally observed that when the free layer switches the magnitude of the noise also changes abruptly. At extreme values of the magnetic field, the noise in the P state (for both orientations of the fixed layer) is nearly the same. The absence of magnetic field dependence when dR/dH is negligible points to a nonmagnetic origin of the $1/f$ noise in the P and AP states.

DISCUSSION

Potential sources for the origin of the field-dependent $1/f$ noise include magnetic impurities in the barrier and spin-dependent charge traps. However, the presence of a specific two-state fluctuator (e.g., a spike in noise power in Fig. 9) at a certain magnetic field in the AP state and its absence at the same field in the P state (or vice versa) rule out magnetic impurities in the barrier. The scaling of α with dR/dH is also inconsistent with spin dependent charge traps. Magnetic domain fluctuations have been implicated as the source of noise in Co/Cu multilayers,¹⁶ silver-permalloy multilayers,¹⁷ and magnetic tunnel junctions.¹² Here we postulate that the $1/f$ noise associated with the reversal of the fixed layer and the telegraph noise due to the switching of free layer are due to thermally activated domain rotation or domain wall hopping between pinning sites.

The characteristic lifetimes of the two levels in the telegraph noise should provide insight into the energetics of domain reorientation. Contributing factors include domain

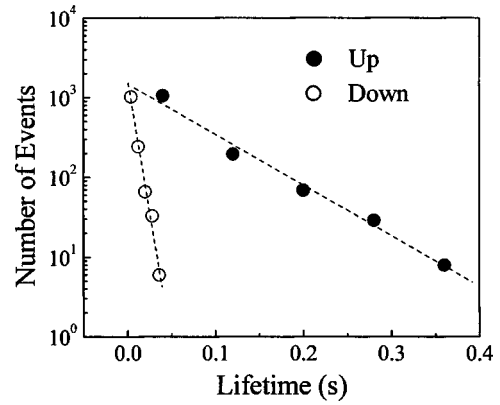


FIG. 10. An example of the probability distributions for the times spent in the up and down states is shown for the telegraph noise graphed in Fig. 8. The dashed lines depict fits to an exponential dependence. Characteristic lifetimes in each state are found to depend strongly on the applied field.

magnetization, anisotropy energies, and local field strengths. The sudden and often irreversible changes we observe in switching character limit the range of fields over which we have been able to obtain data. For similar reasons we have not been able to obtain the temperature dependence of the lifetimes. Since many previously observed two-level system show thermally activated rates¹⁸ we postulate an Arrhenius dependence of the states' characteristic rates. Because the transition rates are strongly affected by the magnetic field, we take the activation energy to be composed of a field-independent term, E , and a Zeeman term, $\Delta\mathbf{m}\cdot\mathbf{H}$, for the fluctuating magnetic moment $\Delta\mathbf{m}$. Hence, the transition rates were assumed to follow

$$\frac{1}{\tau_{i \rightarrow j}(H)} = \frac{1}{\tau_0} \exp\left(-\frac{E \pm \Delta\mathbf{m}\cdot\mathbf{H}}{k_B T}\right), \quad (3)$$

where $\tau_{i \rightarrow j}$ is the lifetime time from state i to state j , and τ_0^{-1} is an attempt frequency. The effective magnetic moment of the two-level system responsible for the telegraph noise in Fig. 8 can be estimated from the ratio of lifetimes, $\tau_{i \rightarrow j}(H)/\tau_{j \rightarrow i}(H) \propto \exp(-2\Delta\mathbf{m}\cdot\mathbf{H}/k_B T)$. The lifetimes at each magnetic field were determined from the probability distributions for the times spent in the up and down states, an example of each is shown in Fig. 10. The distributions are characteristic of a Markovian process, i.e., exponential distributions, $D(\tau) \propto \exp(-t/\bar{\tau})$ where $\bar{\tau}$ is the lifetime time for that state. The magnetic field dependence of the ratio of lifetimes is shown in Fig. 11. A fit to our data results in a lower bound for $\Delta\mathbf{m}$ of $\sim 1 \times 10^7 \mu_B$, where μ_B is the Bohr magneton (determined by assuming $\cos \theta = 1$). This corresponds to an area of about $0.035 \mu\text{m}^2$ in the free layer, whose total area is $0.54 \mu\text{m}^2$. Here we have assumed that the saturation magnetization of the NiFeCo free layer is 910 emu/cm^3 . The fractional change in magnetization is approximately 6.5% whereas the corresponding fractional change in voltage is of order $\sim 0.1\%$. This difference may be accounted for either by small rotations by a single domain or 180° domain walls

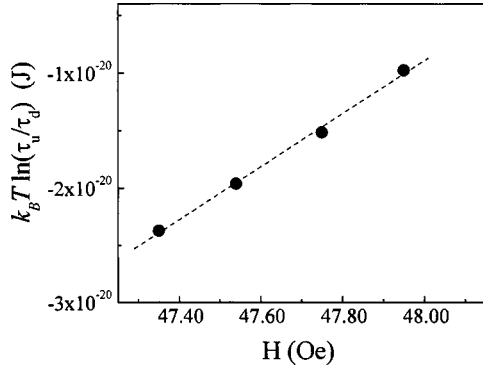


FIG. 11. The ratio of the lifetimes in the up and down states is plotted as a function of magnetic field. The slope of the dashed line is proportional to the size of the fluctuating magnetic moment; see text.

that fluctuate between two energetically favorable configurations and affect the area of adjacent domains.

More generally, one can expect that at any given applied magnetic field a multitude of magnetic domains are fluctuating on comparable time scales, where each fluctuator contributes a Lorentzian spectrum. It is well known that superposition of spectra from effective two-level systems having a broad distribution of activation energies and attempt frequencies leads to $1/f$ noise.^{19,20} In this view our experimental findings suggest that the observed magnetic $1/f$ noise associated with the fixed layer's reversal (Fig. 5) and the Lorentzian plus $1/f$ background associated with the free layer (Figs. 6 and 9) result from two-level systems formed by thermally activated domain wall hopping between sites. The pinning sites could be produced by surface or edge roughness, bulk defects, or random anisotropy due to disorder in the film.

Magnetic fluctuations of this type were shown to be in agreement with the fluctuation dissipation (FD) relation for giant magnetoresistance systems.¹⁶ For MTJ's, Ingvarsson *et al.*,¹² showed that despite hysteresis effects the $1/f$ noise associated the reversal of the free layer was consistent with the FD relation, at least on a given branch of the hysteresis loop. Here we follow a similar analysis to investigate whether the magnetic structure of the fixed layer is in quasi-equilibrium. Owing to the large coupling of the resistance to the external magnetic field provided by the spin dependent tunneling effect in MTJ's, the spectral density of fluctuations in resistance is determined by the spectral density $S_m(f)$ of the fluctuations in magnetic moment m , namely $S_R(f) = (\partial R/\partial m)^2 S_m(f)$. For a sample in thermal equilibrium and exhibiting linear response, $S_m(f)$ is given by the FD relation:

$$S_m = \frac{2k_B T}{\pi \mu_0 f} \chi_m''(f), \quad (4)$$

where μ_0 is the vacuum permeability and χ_m'' is the out of phase magnetic susceptibility.

Lacking χ_m'' data we use the Kramers-Kronig relation to express the dc value of the susceptibility as an integral over all frequencies of the imaginary part of the susceptibility²¹

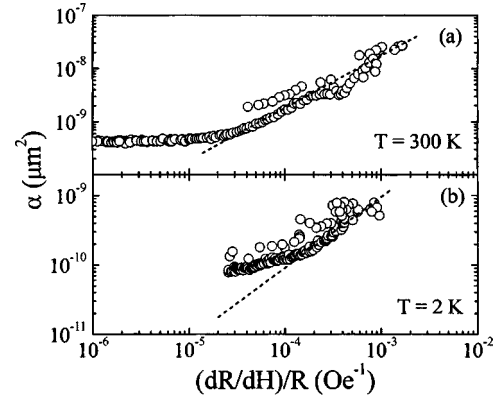


FIG. 12. Dependence of the noise on dR/dH . Data corresponds to the lower branch of the $R(H)$ loops in Fig. 5. As the P \rightarrow AP transition for the fixed layer is approached the noise is observed to scale as the first power of dR/dH , as depicted by the dashed lines. A linear scaling describes the behavior well at high T , but less so at low T . The horizontal part in panel (a) represents the resistance noise background.

$$\chi'(f=0) = \frac{2}{\pi} \int_0^\infty \frac{\chi''(f)}{f} df. \quad (5)$$

Equation (5) can be recast in terms of dR/dH by using the relation $\partial m/\partial H = (\partial m/\partial R)(\partial R/\partial H)$. This leads to an expression for the dc resistance susceptibility given by

$$\frac{\partial R}{\partial H} \Big|_{f=0} = \frac{2m\mu_0}{k_B T \Delta R} \int_0^\infty S_R(f) df. \quad (6)$$

Here we have used $\partial m/\partial R \sim 2m/\Delta R$, where $2m$ and ΔR are the respective changes in magnetic moment and resistance under reversal of the magnetization of the fixed layer.

The noise associated with the reversal of the fixed layer has a spectrum very close to $1/f$ over our experimental frequency range of 1 Hz to 40 kHz, $S_R(f) \propto \alpha R^2/Af^\beta$ where is $\beta \sim 1.0$. If this dependence extends over a sizeable range of f , $f_{\min} < f < f_{\max}$, then the integral in Eq. (6) is simply proportional to α and, hence, the dc value of dR/dH should be proportional to the noise at any fixed frequency. So long as the power β is close to unity the proportionality constant depends only weakly on f_{\min} and f_{\max} and can be estimated from

$$\frac{\partial R}{\partial H} = \frac{2m\mu_0}{k_B T \Delta R} \frac{R^2}{A} \ln\left(\frac{f_{\max}}{f_{\min}}\right) \alpha. \quad (7)$$

The measured values of the noise and of the dc value of dR/dH then provide a quantitative test of the validity of the FD relation and the assumption of quasi-equilibrium.

In Fig. 12 the noise measured at 45 Hz is plotted as a function of the slope dR/dH for the same data shown in Fig. 7. In the region of the fixed layer's P \rightarrow AP transition, the noise measured at $T=300$ K scales as dR/dH to the first power, as predicted by Eq. (7). However, the proportionality constant is close to that predicted by Eq. (7) provided that we take $f_{\max}/f_{\min} \sim 1$, which is not reasonable. Ingvarsson *et al.*¹² found $f_{\max}/f_{\min} \sim 10^9$ in their analysis of noise due to

the free layer. The inconsistency with the FD relation indicates that our system does not achieve quasiequilibrium over a given branch of the hysteresis loop. The fixed layer in our MTJ's is much larger than the free layer and we estimate that $\partial R/\partial m \sim 3 \times 10^{10} \Omega/(\text{Am}^2)$. If the effective area of the fixed layer is taken to be the area of the junction then $\partial R/\partial m$ increases to $4 \times 10^{14} \Omega/(\text{Am}^2)$ and requires $f_{\max}/f_{\min} \sim 10^{50}$, which is also unphysical. At $T=2$ K the noise scales linearly with dR/dH over a very narrow range, if at all.

The lack of quantitative agreement between the measured noise and resistance susceptibility [Eq. (7)] is perhaps not surprising given that the fixed layer is strongly pinned by the underlying magnetic layers, and so is hysteretic and does not exhibit linear response. However, the fact that we see $1/f$ noise and the scaling of the noise with dR/dH over 1.5 decades does suggest that the thermal stability of the fixed layer is an important factor in determining the noise performance of devices.

When the resistive susceptibility is very low, magnetic noise is no longer predominant, and α is dominated by field-independent resistance noise. dR/dH is lowest at large fields where the free and fixed layers are well aligned as well as in the AP orientation; see Fig. 6. Consider, for example, the AP state in Fig. 7. Near $H = -40$ Oe α is constant despite a sharp drop in dR/dH ; that is, the noise is predominately nonmagnetic in origin.

$1/f$ noise and Lorentzian noise in nonmagnetic tunnel junctions are generally believed to be due to fluctuations in the population of localized electron traps in the tunnel barrier.¹⁸ Rogers and Buhrman²² showed that the trapping kinetics in metal-insulator-metal tunnel junctions were thermally activated at high T and were related to transitions between nearly energy-equivalent, but charge-inequivalent, local ionic configurations. A multitude of such traps having a broad distribution of activation energies and attempt rates naturally leads to $1/f$ noise,²³ viz. the Dutta-Horn model. Previous work in MTJ's (Refs. 7–10) also attributed the origin of this noise to charge traps occurring in the barrier or near the interfaces between the barrier and magnetic electrodes. Furthermore, it has been found that α depends on the quality of the junction²⁴ and, in particular, on the oxidation conditions used in forming the barrier.⁸

We have examined the temperature dependence of the nonmagnetic noise in the P and AP states. Figure 13 shows that below 25 K the noise is essentially temperature independent and then increases monotonically with increasing temperature. A linear dependence on temperature, $\alpha(T) \propto T$, is observed for $35 \text{ K} < T < 100 \text{ K}$. Above 100 K a region of sublinear dependence is observed before it sharply increases for temperatures above 250 K.

A plausible explanation for the behavior at low T is a crossover from thermally activated to tunneling kinetics.²² We have checked the bias dependence of the noise at 2 K and verified that this behavior is not due to self-heating. A more convincing test for tunneling and thermally activated kinetics would be to study the temperature dependence of the capture and emission rates of a single charge trap. However, such an analysis was precluded in these junctions because Lorentzian components in the spectrum could not be identified. (We note

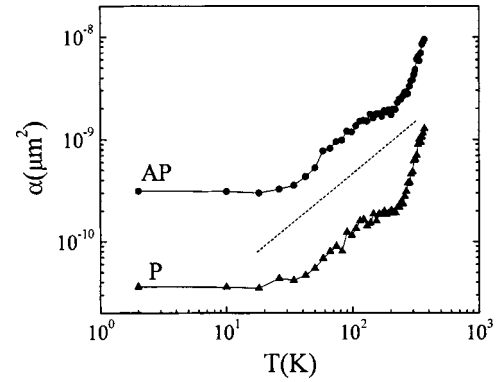


FIG. 13. Temperature dependence of the nonmagnetic $1/f$ noise measured at $H = -40$ Oe in the AP state and $H = 500$ Oe in the P state. The dashed line depicts a linear dependence on T . Data is for a type-A junction having $A = 100 \mu\text{m}^2$.

that in other types of MTJ's for which telegraph noise due to charge trapping could be resolved, the capture and emission rates were thermally activated with activation energies ranging between 100 and 350 meV.) The power spectra over the experimental range of temperatures and frequencies (1 Hz to 10 kHz) were very accurately fit by a power law with slope $\beta \sim -1.0$. In view of the Dutta-Horn model, this implies that the activation-energy density of states is relatively constant and large, even for $E_a \lesssim 100$ meV. Indeed, the analysis shows E_a is flat out to ~ 0.5 eV and then begins to increase to at least 0.7 eV. The rapid rise in α above ~ 250 K may be due to an increase in the number of microscopic fluctuators active in our bandwidth. Alternatively, the magnitude of the resistance fluctuations due to individual traps may be temperature dependent. In the definition of $\alpha(T)$, the temperature dependence of the tunneling resistance is normalized out, but this has a comparatively minor effect.

Further investigations are necessary to have a realistic model for how defects in the tunnel barrier material lead to carrier trapping and resistance fluctuations in MTJ's. In the model developed by Rogers and Buhrman to explain data in Nb_2O_5 tunnel junctions,²² the kinetics of capture and emission are governed by ionic reconfigurations at a single point defect, assumed to be an oxygen vacancy. The ionic-reconfiguration model is reminiscent of the model often used to describe the low-temperature properties of glasses.^{25,26} Since in the barrier region there are very strong electrochemical gradients, Roger and Buhrman considered that displacement of an oxygen vacancy by a distance of order the lattice spacing would dramatically affect its occupancy; thus causing instantaneous electron capture or emission. In our MTJ's, the tunnel barrier is amorphous but may not be stoichiometric Al_2O_3 . If this type of defect also dominates in our tunnel barriers, then a likely ionic reconfiguration would be an oxygen vacancy moving between nearly equivalent sites. Our temperature data (Fig. 13) would indicate that reconfiguration proceeds by thermal activation at high T and by ionic tunneling at low T . The broad distribution of activation energies that we find from the Dutta-Horn analysis is also consistent with the amorphous nature of the barrier material.

Finally, we comment on the relative magnitudes of the nonmagnetic noise in the P and AP states. α is generally observed to be larger in the AP state, often by a factor of 2, although exceptions do occur (see Fig. 6). We find that the difference depends on the applied magnetic field, and more specifically on the value of dR/dH at which the noise is measured for each state. For example, the noise in Fig. 13 was measured at $H = -40$ Oe (AP state) and at $H = 500$ Oe (P state). These fields correspond to a local minimum in dR/dH for the AP state and a global minimum in the P state. In this case the difference in α is a factor of ~ 10 . If the P state noise is measured at $H = 40$ Oe, the difference is smaller due to an increased background of magnetic noise. Preliminary results also indicate that the difference is bias dependent; that is, the P state $\alpha(V)$ is nearly independent of V , whereas in the AP state it decreases by a factor of ~ 2 as V is increased to 300 mV.

The general picture then is that resistance noise at any given field is a superposition of magnetic and nonmagnetic noise. Which mechanism is dominant depends on any number of factors, including the quality of the barrier, interface roughness, and the thermal stability of magnetic layers. We note that our data was collected from junctions with a variety of sizes ($0.45\text{--}100\ \mu\text{m}^2$). Although we have not examined the influence of the junction size systematically, we do not find significant differences in the general field or temperature dependences of α nor in the magnitude of the nonmagnetic portion of α at room temperature.

CONCLUSION

Noise in magnetic tunnel junctions has its origin in thermal, shot, magnetic and nonmagnetic mechanisms. Since practical applications require biasing the junction, both thermal and shot noise will set the ultimate sensitivity of devices based on MTJ's. The power spectrum of thermal and shot noise in MTJ's is in good agreement with the shot noise relation [Eq. (1)] and is independent of frequency out to very high frequencies.

At low frequencies there is additional noise that exhibits a $1/f$ power spectrum and is due to a superposition of (1) thermal magnetization fluctuations in the magnetic electrodes that couple to the resistance via the spin-dependent tunneling effect, and (2) tunnel barrier height fluctuations due to charge trapping in or near the oxide barrier. The magnetic noise is largest at applied fields at which the dc resistance susceptibility peaks; i.e., at fields where the free and pinned magnetic electrodes undergo reversal. Random telegraph noise associated with the reversal of the free layer indicates that even in our submicron scale MTJ's magnetic instability exists in the form of domain wall hopping between pinning sites. The $1/f$ noise associated with the fixed layer reversal is linearly pro-

portional to the dc resistance susceptibility over an extended range of fields. Although this linear scaling is consistent with the fluctuation dissipation theorem for thermal magnetization fluctuations, there is quantitative disagreement in the magnitude indicating that the magnetization fluctuations are not in equilibrium. Magnetic $1/f$ noise can also be present at the low fields typically used for field sensing and nonvolatile magnetic random access memory (MRAM) applications. Whether magnetic noise is a performance limiting factor in these applications depends on magnitude of the dc resistance susceptibility and the thermal stability of the magnetic layers. Our results also highlight the importance of including thermal magnetization fluctuations and disorder in micro-magnetic simulations that aim to reveal the magnetization reversal process in MTJ elements.

When the dc resistance susceptibility is very low, magnetic noise no longer predominates and $1/f$ resistance noise due to charge trapping in the oxide barrier is evident. The magnitude of this noise seems to depend in a nontrivial way on the quality of the barrier. In MTJ's that exhibit favorable MR characteristics, the noise magnitude is found to increase with temperature above ~ 25 K. Below 25 K, the noise is temperature independent. We propose a model for the noise similar to the one applied to metal-insulator-metal tunnel junctions;²² namely, ionic reconfiguration of oxygen vacancies that form a trap in the amorphous Al_2O_3 oxide barrier. A superposition of many independent traps having a broad distribution of activation energies naturally leads to the $1/f$ power spectrum that is observed over a very broad range of temperatures. Our temperature data also suggests that the population kinetics of traps is governed by reconfigurations that proceed by thermally activation at high temperatures and by ionic tunneling at low enough temperatures.

The magnitude of the nonmagnetic $1/f$ noise in our MTJ's can be compared to those of Park *et al.*¹¹ where a scaling of the noise magnitude with the RA product was found. In our MTJ's, $RA = 6\ \text{k}\Omega\ \mu\text{m}^2$ and the value of α at $T = 300$ K in the P orientation lies between 10^{-10} to $10^{-9}\ \mu\text{m}^2$. This range of values is only a factor of 2 lower than those reported in Ref. 11 for MTJ's having $RA \sim 1\ \text{M}\Omega\ \mu\text{m}^2$. Extrapolating their scaling down to $6\ \text{k}\Omega\ \mu\text{m}^2$ yields $\alpha < 10^{-12}\ \mu\text{m}^2$, which is much smaller than we observe. The scaling of the noise with the resistance-area product appears nontrivial and our results suggest that nonmagnetic $1/f$ noise may have a lower bound ($\sim 10^{-10}\ \mu\text{m}^2$) for $RA < 1\ \text{M}\Omega\ \mu\text{m}^2$.

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