

Low-frequency magnetic noise in magnetic tunnel junctions

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We studied low-frequency noise in NiFe-Al₂O₃-NiFe based magnetic tunnel junctions (MTJ's) with and without a hard-axis bias field. The $1/f$ noise is observed to be magnetic-field dependent and reduced with the application of hard-axis bias fields, attributed to thermally activated magnetization fluctuations in the magnetic electrodes. A linear dependence of noise on derivative of magnetoresistance has been observed, and the magnetic-field noise for MTJ sensing elements is defined and evaluated to be as low as 60 nT $\mu\text{m}/\text{Hz}^{1/2}$.

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The study of noise of magnetoresistive materials is important for understanding the performance of spin-dependent electronic devices as well as the physical processes that govern their magnetic properties. There are many processes that can contribute to the noise of a magnetoresistive based device. Based on its physical origin, the noise is categorized into three types. Thermal resistance noise, also known as Johnson or Nyquist noise, results from a thermal smearing of the density of states near the Fermi level. Shot noise is due to the stochastic nature of electron transport with an applied current. The third kind of noise, $1/f$ noise, also called flicker noise or excess noise, arises from the coupling of electronic processes with magnetization fluctuations.^{1,2} The first two noise sources are frequency independent, while $1/f$ noise scales inversely with frequency, as suggested by its name. Usually $1/f$ noise is an indirect noise and manifests itself as resistance fluctuations in different physical systems in low-frequency range. As examples, resistance fluctuations in two-dimensional electron system in semiconductor heterostructures³ and high- T_c superconductor⁴ have different physical origin. Due to its nature, there is not a universal explanation to physical origin of $1/f$ noise.

In this paper we are interested in magnetoresistance (MR) fluctuations at low fields in Py-Al₂O₃-Py (Py=Permalloy, Ni₇₉Fe₂₁) based magnetic tunnel junctions (MTJ's). This spin-dependent system shows great potential for high sensitivity, low-noise magnetic-field sensing applications, due to its low saturation field and high MR ratio (defined as $\Delta R/R$, where ΔR and R are the maximum resistance change and the minimum resistance, respectively). In addition, the exponential dependence of junction resistivity on the barrier thickness allows for a large degree of control over device resistance. A typical tunnel junction consists of two ferromagnetic (FM) metal layers separated by an ultrathin insulating barrier. Changes in the relative magnetization orientations between these two FM layers in applied magnetic field(s) determine the final resistance, i.e., MR. Although many fundamental aspects of this system, including magnetization reversal processes,⁵ scattering mechanisms,⁶ and electron transport behavior have been studied in detail, the low-frequency noise characteristics have not been fully explored.

In a recent work, Ingvarsson *et al.* have studied magnetic noise produced by magnetization fluctuations in MTJ's (Ref. 7). These fluctuations have been attributed to the thermally excited hopping of magnetic domain walls between pinning

sites. Such fluctuations determine a fundamental noise limit for MR-based devices.^{8,9} However, Reed *et al.* measured $1/f$ noise in MTJ sensors and observed that low-frequency sensor noise is dominated by resistance fluctuations in the tunnel barrier, and that these resistance fluctuations are due to charge trapping in the barrier.¹⁰ In order to clarify the physical origin and evaluate the noise level of $1/f$ noise in MTJ's, we conducted a systematic study of low-frequency noise in high-quality MTJ sensors under different magnetic environment, i.e., with and without a hard-axis bias field perpendicular to the magnetic easy axis of the sample. The hard-axis bias modulates both the MR response and noise. The obtained results clearly show that the magnetic noise due to magnetization fluctuations in the magnetic electrodes is the dominant noise source in our MTJ samples, and the field noise level of MTJ-based devices is defined.

The MTJ's studied in this work were deposited on thermally oxidized Si wafers using a multitarget high-vacuum magnetron sputtering system (base pressure 2×10^{-8} Torr). The layer structure is Pt(30 nm)/Py(3 nm)/FeMn(13 nm)/Py(6 nm)/Al₂O₃/Py(12 nm)/Al(49 nm). Here Py(6 nm), Al₂O₃, and Py(12 nm) are the pinned, insulating barrier, and free layers, respectively. The samples were patterned using standard optical lithography followed by ion-beam etching to make micron-size junctions and contact pads for both voltage and current leads. A 150-nm-thick gold layer was deposited over the active areas to prevent contamination and create low-resistance contact to the junction. An easy-axis direction in the samples has been defined during sputtering and enhanced by a process of postannealing. Cross-sectional transmission electron microscopy (TEM) has revealed that roughness at the Al₂O₃-Py interfaces is only 0.3–0.4 nm and that the barrier is virtually pinhole free. Growth specifications and MR properties of our MTJ samples were described in detail in a previous work.¹¹

The noise measurements were performed in a double shielding box using the setup as shown in Fig. 1. Two static magnetic fields H_e , H_h are provided by crossed pairs of toroidal electromagnets. The measurement system including MTJ's under investigation and electromagnets are magnetically shielded using a box made of high-permeability μ metal. A battery and a variable resistor provide a dc sense current to the device. The voltage V across the junction is fed into a battery-powered low-noise preamplifier with a gain of 1000–10 000, and the amplified output is processed using a

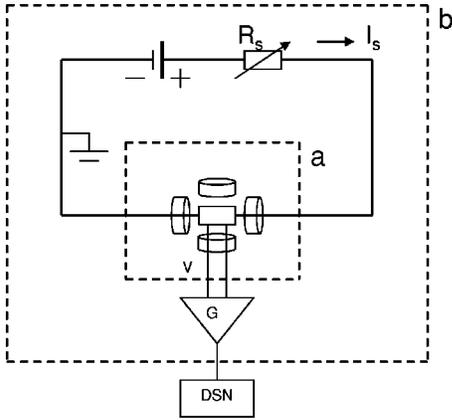


FIG. 1. Experimental setup for noise measurements. The magnetic-sensitive parts, two crossed pair of electromagnets and MTJ device are placed in a magnetic-shielding box *a*. Electrical parts including power battery, bias resistance, and preamplifier are shielded in an aluminum box *b*.

HP35670A dynamic signal analyzer to obtain the voltage power spectral density (PSD). During measurements, the electrical environment of the setup is shielded within another metal box *b*.

During our measurements, the easy-axis field H_e is swept with an increment of 0.5 Oe. At each field, the junction is allowed to equilibrate for 1 min before the noise and resistance are measured simultaneously. Low dc sense currents were applied to avoid interference from any associated magnetic fields or current-induced noise. It is noted that due to the history dependence of the ferromagnetic materials in MTJ's, there is often a noticeable difference between the noise data of the initial measurement and those after cycling the junction several times in an applied field. The noise and resistance data presented here are those measured after the junction is swept through several field loops with an applied voltage bias.

Although many samples with different size and shape have been examined for this study, we will focus on the results of three representative samples with rectangle in shape. In order to verify that the noise detected here is indeed from MTJ's examined, not the environment or peripheral equipments, we measured noise as a function of applied voltage across the junction. The typical noise curves for sample I with dimensions $12 \times 24 \mu\text{m}^2$ are displayed in Fig. 2. It can be seen that $1/f$ noise dominates in low frequency, and its magnitude increases with the applied bias voltage V . The voltage noise spectrum S_V at a frequency of 10 Hz is plotted as a function of bias voltage in the inset, and is scaled as the square of the dc bias voltage. This result indicates that the $1/f$ noise can be attributed to resistance fluctuations in the MTJ's, and can therefore be characterized by Hooge's formula:¹²

$$S_V = \frac{\alpha V^2}{N f^\gamma}, \quad (1)$$

where α is the material-specific Hooge parameter, N is the number of fluctuators, and γ is the exponent of the $1/f$ noise

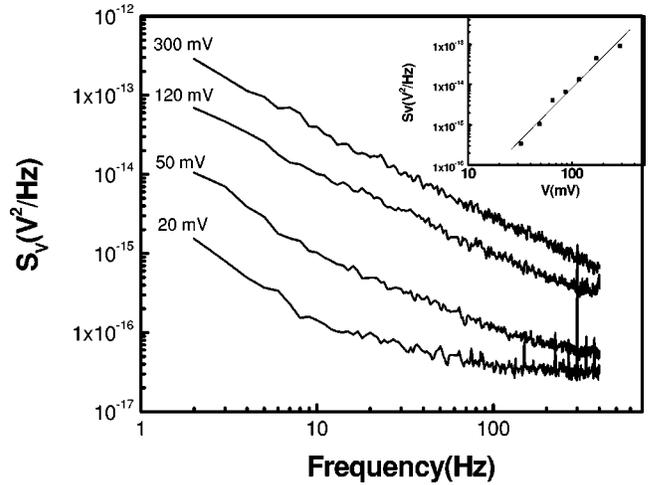


FIG. 2. Voltage power spectral density S_V in frequency domain under different bias voltage V on sample. Inset is S_V measured at frequency $f = 10$ Hz as a function of bias voltage.

spectrum and it determines the exact frequency dependence of the $1/f$ noise. This voltage-dependent noise is an experimentally important result in that it confirms that the noise obtained is intrinsic to the junction under investigation rather than being the result of an experimental artifact.

We measured the voltage noise spectra $S_V(f)$ for the same junction with a sense current of $40 \mu\text{A}$ under different easy-axis fields. Shown in Fig. 3 are the representative noise curves in the frequency range of 1–400 Hz under three fields. Within the range of sweeping field, only the switching of top free magnetic layer can be seen. In this configuration, no hard-axis bias is applied, leading to a highly hysteretic MR response, which is confirmed by two sharp resistance transitions seen in the inset of Fig. 3. The junction exhibits

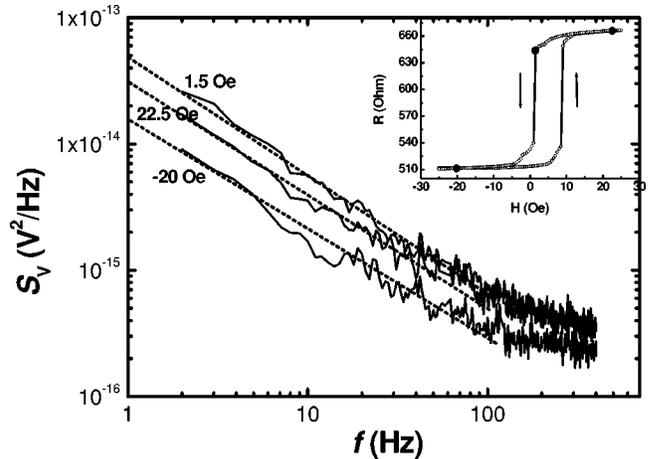


FIG. 3. Voltage noise spectrum vs frequency spectrum at different easy-axis fields for a $24 \times 12 \mu\text{m}^2$ junction without hard-axis bias fields. The dash lines are drawn to display the low-frequency $1/f$ noise for different sweeping easy-axis fields. Inset is the magneto-resistance curve as a function of sweeping field $R(H)$. The noise spectra and resistance are measured simultaneously. Three big dots on $R(H)$ curve are the points corresponding to noise spectra in field, respectively.

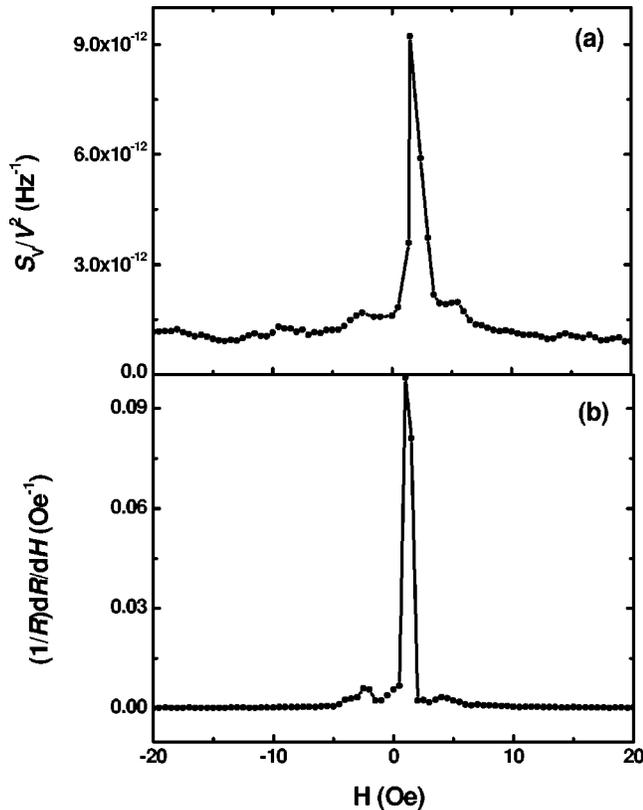


FIG. 4. The voltage-normalized noise spectra (a) and the derivative of the $MR(H)$ (b). The noise value is obtained by fitting the low-frequency noise and extrapolating $S_V(f)$ to 1 Hz with field ramping down from AP to P state.

an MR of 31% and the antiparallel (AP) to parallel (P) state transition occurs at $H_e = 1.5$ Oe. As shown in Fig. 3, $1/f$ noise is significant up to ~ 100 Hz (the cutoff frequency), above which the noise spectra are frequency independent and dominated by thermal and shot noise, i.e., $S_V(f) = 2R(2k_B T + eV)$, where k_B is Boltzmann constant and e the electron charge. Fitting the noise curves in low-frequency range according to Eq. (1), we obtained the frequency exponent $\gamma = 0.85 \pm 0.06$ for all of fields. The deviation from $\gamma = 1$ is attributable to the fact that the lifetimes of two-level systems are not uniformly distributed over the measurement range of our experiment.^{2,12}

It can be seen from Fig. 3 that noise spectra are identical in the region $H_e < -5$ Oe, where the sample is in P state; the same is true in AP state ($H_e > 10$ Oe). The junction exhibits a larger overall noise figure in the latter state, due to the increase in the voltage across the junction at AP state. To further quantify the noise as a function of field, we have fitted the low-frequency noise data and extrapolated the noise curve to 1 Hz. The results are normalized with respect to bias voltage V^2 and are plotted as a function of applied field, shown in Fig. 4(a). In the vicinity of the magnetic switching (AP to P) at $H_e = 1.5$ Oe, the magnitude of the $1/f$ noise increases dramatically by one order of magnitude in the form of a sharp peak. The same noise behavior has also been observed with field sweeping from P to AP at $H_e = 10.5$ Oe (not shown here). This strongly suggests the

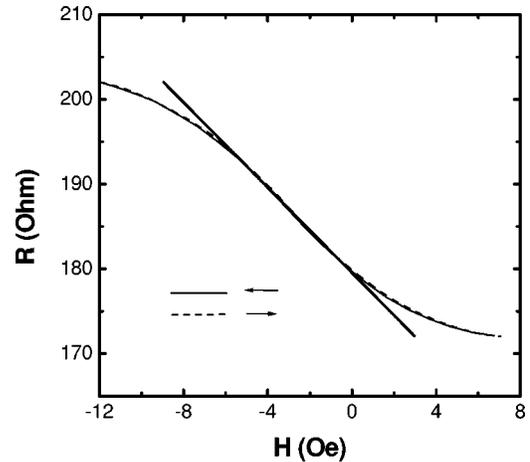


FIG. 5. Magnetoresistance as a function of sweeping easy-axis fields under an applied hard-axis bias field 6 Oe perpendicular to easy axis of a $36 \times 24 \mu\text{m}^2$ MTJ. The dashed line is drawn to show the linearity of the MR response at the midpoint of switching region. The arrows display the direction of the sweeping field.

dominance of magnetic fluctuations in origin within the transition region for our MTJ's. Additionally, the normalized noise levels in P and AP states are flat and roughly equal to each other, implying that there is little hint of instability in the AP state as compared with the P state.

The field dependence of noise displayed in Fig. 4(a) is seen to be remarkably similar to that of the derivative of the MR, which is plotted for comparison in Fig. 4(b). This similarity has been observed previously in both giant magnetoresistive (GMR)^{9,13} and anisotropic magnetoresistive (AMR) (Ref. 9) systems. Neither spin-dependent trapping in the barrier layer nor current-induced fields in the junction can explain this noise behavior,¹⁴⁻¹⁷ while a model of thermally activated hopping of domain walls between pinning sites provides a plausible explanation.⁷ The consistency between our results and those observed in other magnetoresistive systems implies that thermally activated magnetization fluctuations often dominate the noise in such systems, especially in the regime where dR/dH is large. Far from the magnetic transition, as dR/dH approaches zero, the noise becomes constant, indicating that field-independent resistance noise sources become significant.

In order to confirm that the noise in our MTJ device originates from the magnetization fluctuations in the free electrode, we studied the low-frequency noise behavior under a hard-axis bias field H_h . It is known that the application of a hard-axis bias field can change the magnitude as well as orientations of magnetization in free electrode, resulting in a linear nonhysteresis MR response in the transition region.¹⁸ Figure 5 displays such a typical MR response under a hard-axis bias $H_h = 6$ Oe for our MTJ's. The MR curve is observed to change linearly between states, with a minimum hysteresis of 0.5 Oe at the midpoint of switching region. This MR behavior indicates a continuous and smooth change in the magnetization direction of the free FM layer. Shown in Fig. 6 are the noise value and resistance as a function of H_e at a fixed $H_h = 8$ Oe for another sample II on the same wafer.

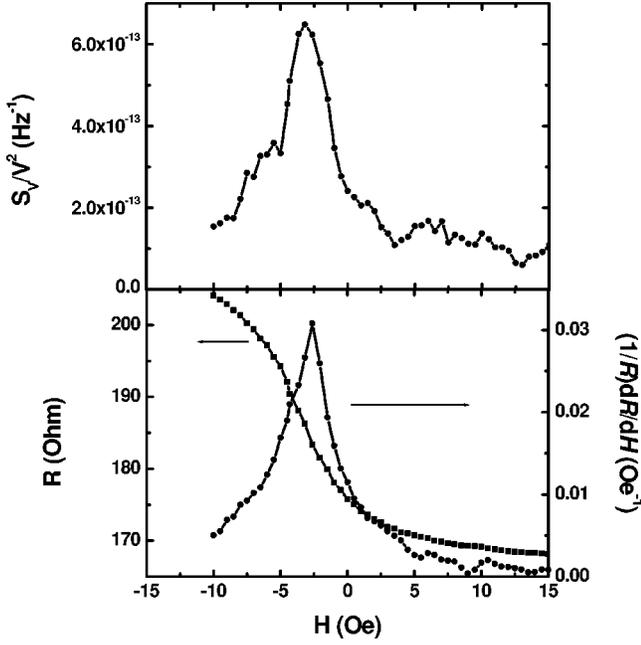


FIG. 6. The voltage-normalized noise in field spectra (a) and the corresponding $R(H)$ curve and its derivative (b) with hard-axis bias field $H_h = 8$ Oe. The noise value is taken from extrapolating low-frequency noise to 1 Hz.

A strong correlation between $1/f$ noise level and the derivative of MR [$= (1/R)dR/dH$] is again observed, with both exhibiting a broad peak in transition region, as shown in Fig. 6(b). The maximum noise level of the peak is greater than those measured at fully saturated states by a factor of 4. However, this value is an order of magnitude less than that without hard-axis field [Fig. 4(a)]. After normalizing to account for the different sample sizes, the noise amplitude is still a factor of 3 smaller. The reduction of noise level indicates that the switching occurs by a process of coherent rotation, and hard-axis field is established to stabilize the magnetic domain structure of the free electrode.

To quantify the magnetic noise in our sample, we plotted the normalized noise value versus the derivative of MR, as shown in Fig. 7. $S_V^{1/2}/V$ depends on $(1/R)dR/dH$ with a roughly linear relationship, and therefore can be scaled as the first power of $(1/R)dR/dH$:

$$\left(\frac{S_V}{V^2}\right)^{1/2} = \left(\frac{S_V(0)}{V^2}\right)^{1/2} + k \left(\frac{1}{R} \frac{dR}{dH}\right). \quad (2)$$

Here $(S_V(0)/V^2)^{1/2} = 1.5 \times 10^{-7} \text{ Hz}^{-1/2}$ is the noise level of which $(1/R)(dR/dH) = 0$. This noise represents a nonmagnetic fluctuation contributing to $1/f$ noise, providing a fluctuation background in MTJ's. To extrapolate this nonmagnetic noise level to 1 kHz (the range of $1/f$ noise in our samples), $S_V(0) \sim 3 \times 10^{-17} \text{ V}^2/\text{Hz}$. This noise value is equivalent to the white noise of a resistance of 500Ω at room temperature, which is close to our junction resistance ($\sim 200 \Omega$). This indicates that the nonmagnetic noise in our MTJ's is mostly originated from the thermal resistance fluctuations, therefore representing the ultimate fluctuation back-

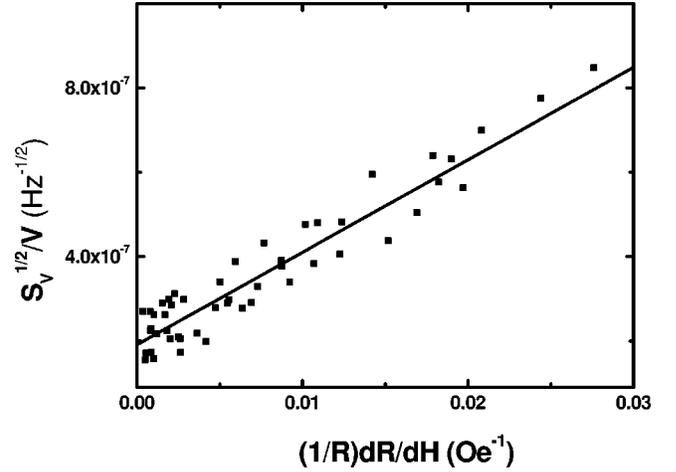


FIG. 7. The noise $S_V^{1/2}/V$ vs the derivative of MR of Fig. 6. The solid line is the linearity fitting. The intercept $S_V(0)^{1/2}/V$ is about $1.5 \times 10^{-7} \text{ Hz}^{-1/2}$ and the slope $k = 1.9 \times 10^{-5} \text{ Oe}/\text{Hz}^{1/2}$.

ground in MTJ's. It should be pointed out that the validity of Eq. (2) rests on the assumption that the magnetic noise is the dominant source and does not couple with other field-independent fluctuations. In Eq. (2), $k = 1.9 \text{ nT}/\text{Hz}^{1/2}$ is the slope of the fitting line. According to the definition of magnetic-field noise,

$$S_H \equiv (\partial H / \partial V)^2 S_V = \frac{1}{\left(\frac{1}{R} \frac{\partial R}{\partial H}\right)^2} \frac{S_V}{V^2}.$$

Thus k is the representative of the field noise level $S_H^{1/2}$, vice versa, the field noise is the first power of voltage noise by $d(MR)/dH$. Considering the noise level obtained here is sample-size dependent in Eq. (1), we scale the field noise level in our MTJ by sample area A , $S_H^{1/2} = k \times \sqrt{A} \approx 60 \text{ nT } \mu\text{m}/\text{Hz}^{1/2}$.

In conclusion, we have measured low-frequency $1/f$ noise and magnetoresistance simultaneously in Py- Al_2O_3 -Py magnetic tunnel junctions with different configurations. The observed $1/f$ noise is dependent on the derivative of magnetoresistance, a result of thermally activated magnetization fluctuations in the free FM electrode. The application of a hard-axis biasing linearizes the MR response, and stabilizes magnetic domain structure in the according layer. We scale the noise as the first power of MR response, thus the magnetic field noise for MTJ sensing units is defined and evaluated to be $60 \text{ nT } \mu\text{m}/\text{Hz}^{1/2}$.

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