AIP Applied Physics Letters

Low frequency noise in highly sensitive magnetic tunnel junctions with (001) MgO tunnel barrier

Dipanjan Mazumdar, Xiaoyong Liu, B. D. Schrag, Matthew Carter, Weifeng Shen, and Gang Xiao

Citation: Applied Physics Letters **91**, 033507 (2007); doi: 10.1063/1.2754352
View online: http://dx.doi.org/10.1063/1.2754352
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/91/3?ver=pdfcov
Published by the AIP Publishing

Low frequency noise in highly sensitive magnetic tunnel junctions with (001) MgO tunnel barrier

Dipanjan Mazumdar[a)]
Physics Department, Brown University, 182 Hope St., Providence, Rhode Island 02912

Xiaoyong Liu, B. D. Schrag, and Matthew Carter
Micro Magnetics, Inc., 421 Currant Road, Fall River, Massachusetts 02720 and Physics Department, Brown University, 182 Hope St, Providence, Rhode Island 02912

Weifeng Shen and Gang Xiao
Physics Department, Brown University, 182 Hope St, Providence, Rhode Island 02912

(Received 8 May 2007; accepted 11 June 2007; published online 18 July 2007)

Low frequency voltage noise was measured in highly sensitive magnetic tunnel junctions with MgO tunnel barrier. The voltage noise is observed to scale linearly with the magnetic field sensitivity. Fluctuations in noise, possibly due to local domain nucleation or annihilation inside the free layer, are also observed. Results indicate that an external hard-axis bias field can significantly suppress the magnetization fluctuations of the free layer and lower the magnetic field noise. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2754352]

Interest in magnetic tunnel junctions (MTJs) received a boost in 2004 with the publication of two articles reporting the fabrication of high magnetoresistance (MR > 100%) devices with (001) MgO insulating barrier.[1,2] The key to achieve such high MR values was the experimental realization of spin-coherent tunneling, which was theoretically predicted for ferromagnetic electrodes that are lattice matched with a textured (001) MgO barrier.[3,4] This discovery has already made a direct impact on the magnetic data storage, magnetic random access memory, and the MR sensor industry.

From a magnetic field sensing point of view, the magnetic field sensitivity and magnetic field noise will ultimately dictate whether this high MR translates into highly sensitive magnetic sensors. The field sensitivity is defined as $s=1/R(dR/dH)$, where R is the resistance of the device and H is the external magnetic field. Voltage noise, on the other hand, does not have such a simple relation. The low-frequency (LF) voltage noise spectrum in a MTJ displays a $1/f^{\gamma}$ ($0.8<\gamma<1.4$) behavior up to a material specific knee frequency f_k, beyond which the noise becomes white (frequency independent). Empirically, the $1/f$ noise spectrum is well described by Hooge's relation, $S_v=\alpha V^2/Nf^{\gamma}$.[5] Here, S_v is the power spectral density, α is the material specific Hooge constant, V is the voltage bias of the MTJ, and N represents the number of fluctuators, which usually scales with the volume of the noise generating active component. According to the Dutta-Dimon-Horn model,[6] $1/f$ noise is considered as a superposition of two-level noise spectra with a broad distribution of activation energies.

Noise characterization of MgO MTJs is especially important due to the high sensitivity that these devices exhibit when used as magnetic field sensors.[7–9] In this work, we focus primarily on the LF $1/f$ noise arising from fluctuations of the magnetization of the MTJ free layer. This noise is both interesting and important because these magnetization fluctuations persist at all temperatures, irrespective of the choice of ferromagnetic materials and fabrication conditions. Detailed characterization of the magnetization noise will go a long way in determining the future of these devices. In this work, we investigate in detail the effects of an external hard bias field on the magnetic noise and show that the application of such a bias field can lower the LF magnetic field noise, improving sensor performance.

MTJ spin valves with the following layer structure were prepared using magnetron sputtering on thermally oxidized Si wafers (units in angstroms): Ta (300)/$Co_{50}Fe_{50}$ (20)/IrMn (150)/$Co_{40}Fe_{50}$ (20)/Ru (8)/$Co_{40}Fe_{40}B_{20}$ (30)/MgO (16)/$Ni_{79}Fe_{21}$ (30)/Ta (100)/Ru (50). A schematic diagram is shown in the inset of Fig. 1(a). Details of our sample fabrication methods are reported elsewhere.[10] The junctions studied in this work had areas of 100–300 μm^2. The 16 Å thick MgO barrier provided optimal resistance and MR characteristics for our samples. NiFe was chosen for the free layer because of its well known soft magnetic properties. A synthetic antiferromagnet (CoFe/Ru/CoFeB) was used as the pinned layer and was strongly exchange biased with the antiferromagnetic IrMn layer. The exchange bias field for the pinned $Co_{40}Fe_{40}B_{20}$ layer was measured to be 1.5 kOe using a vibrating sample magnetometer.

Noise measurements were performed in an electrostatically shielded box to suppress spurious environmental noise sources. Each four-lead MTJ device was mounted on a custom-made electronics board equipped with a dc blocking capacitor and two low-noise preamplifiers. The amplified noise voltage was fed to an HP-35760A spectrum analyzer operating in cross-correlation mode. The junctions were biased to a relatively high voltage (200 mV) to ensure that the noise spectra exceeded the amplifier noise floor ($S_v \approx 5 \times 10^{-17}$ V^2/Hz). Data were measured from 1 Hz to 51.2 kHz.

In order to translate the measured voltage noise into an equivalent field noise, accurate field sensitivity measurements were also performed. The slope dR/dH was measured directly by applying a 1 Oe rms ac field along the easy axis of the MTJ and measuring the corresponding voltage re-

[a)]Electronic mail: mazumdar@physics.brown.edu

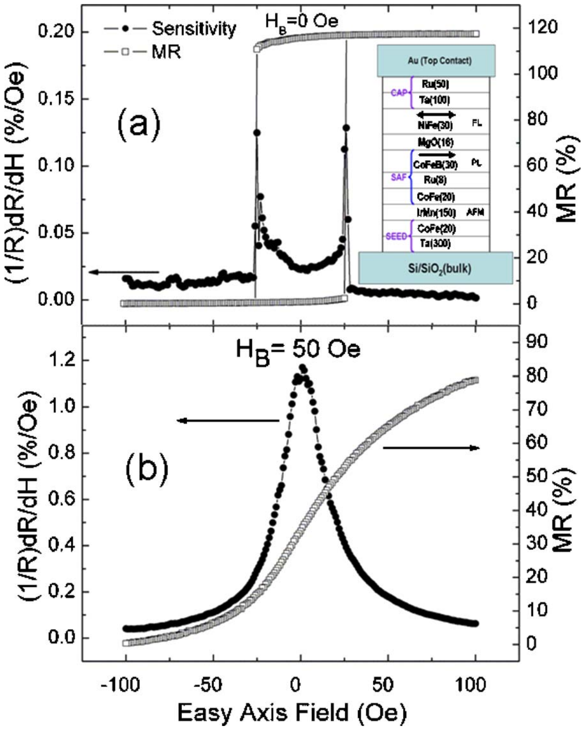

FIG. 1. (Color online) Sensitivity and magnetoresistive response of a typical MTJ in (a) memory state and (b) sensor state. Inset of (a) shows the schematic MTJ layer structure.

sponse with a lock-in amplifier. In addition, *R*-*H* measurements were also performed using a standard four-probe method.

Knowing *s*, and assuming that S_v has no nonmagnetic component, we can define a characterization parameter called the magnetic field noise S_H which is given by the simple relation

$$S_H = S_v^{0.5}/Vs. \tag{1}$$

This magnetic field noise value is a measure of the magnetic noise floor of the sensor. Typically it is expressed in units of $\mathrm{nT/Hz^{0.5}}$. A low magnetic field noise value is a highly desirable characteristic of a magnetic field sensor.

Figure 1 plots the sensitivity and MR of a representative MTJ as the external easy-axis field H_E was varied. In the memory state configuration [Fig. 1(a)], the free layer (FL) and the pinned layer (PL) magnetization directions are either parallel or antiparallel to each other, and no external hard-axis bias field (H_B) is applied. Even though the MR is high (≈120%), a maximum sensitivity of only about 0.15%/Oe was obtained over a very small field range. On the other hand, when the FL and PL orientations are perpendicular to each other [Fig. 1(b)], sensitivity in excess of 1%/Oe was obtained over a relatively wide field range. This configuration, called the sensor state, can be achieved by applying a sufficiently strong hard-axis bias field (H_B), which was equal to 50 Oe in this case. So, at a large fixed hard bias field a wide range of sensitivity values can be obtained, as shown in Fig. 1(b). Investigation into the noise at different hard-axis bias fields will be the subject of discussion for the remainder of this letter.

Figure 2 shows the correlation between the normalized voltage noise ($\delta V/V$) measured at 100 Hz and the field sensitivity for a junction in the sensing state under a biasing

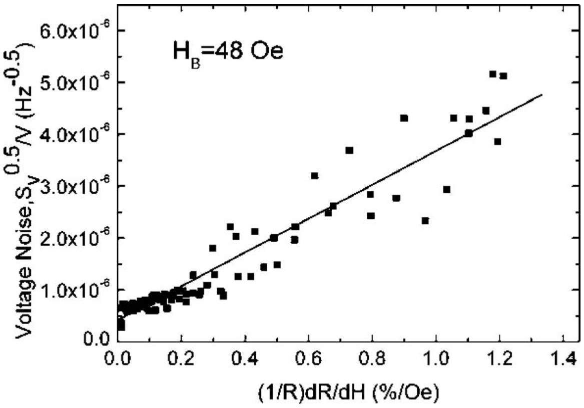

FIG. 2. Normalized voltage noise ($\delta V/V$) at 100 Hz vs sensitivity(s) plot at a specific hard-axis bias field of 48 Oe. A linear fit gives an intercept of $4\times10^{-7}\ \mathrm{Hz^{-0.5}}$ and a slope $\langle S_H\rangle$ of 34.4 nT. The intercept gives the nonmagnetic contribution to the noise and the slope is a measure of the average magnetic field noise.

field of H_B=48 Oe. The noise versus sensitivity plot ($\delta V/V$ vs *s*) allows us to characterize both the nonmagnetic and magnetic noise simultaneously. For all the junctions studied, the voltage noise is seen to scale linearly with the field sensitivity. A linear fit to the plot gives an intercept of $4\times10^{-7}\ \mathrm{Hz^{-0.5}}$. This is the nonmagnetic contribution to the overall noise and this sensitivity-independent noise value is typically less than 10% of the total noise at *s*=1%/Oe. Therefore when the MTJ is operating at high sensitivities, voltage noise is predominantly magnetic in origin. The slope of the linear fitting, $\langle S_H\rangle$=344.8 μOe or 34.5 nT, represents the average magnetic field noise value for all the data points in Fig. 2. Reducing this value is a critical objective for application purposes.

We also observe large fluctuations in $\delta V/V$, especially at high sensitivities. For instance, in the sensitivity range between 0.9%/Oe and 1%/Oe, $\delta V/V$ fluctuates from 4×10^{-6} to $2\times10^{-6}\ \mathrm{Hz^{-0.5}}$, a twofold fluctuation over only a 10% change in sensitivity. These fluctuations do not show up as Barkhausen noise in the MR response nor as random telegraph noise in the noise spectra. It indicates that small and random magnetization changes do occur during the coherent rotational motion of the FL. For example, during coherent rotation, small domains can nucleate (or annihilate) at random locations, specially around edges, defects, and impurity sites. As a result, these magnetization changes can bring about fluctuations in the noise spectrum. Better thin-film deposition and annealing processes could help in reducing such magnetic instabilities.

In our systematic study of the noise-sensitivity plots as a function of the external hard-axis bias field, we found that the magnetic field noise to be field dependent. In Fig. 3, we plot the extracted field noise values and the voltage noise at *s*=1%/Oe as a function of H_B. The hysteretic region has been shaded out and the MTJ achieves a sensing state configuration outside of this region. In the memory state configuration (H_B=0 Oe), $\langle S_H\rangle$ is high due to the low sensitivity of the MTJ. However, as H_B is increased, sensitivity increases and we observe a sharp reduction in $\langle S_H\rangle$ at an average rate of ≈4 nT/Oe until H_B=25 Oe. At this point the noise values hit a knee. Beyond this point, a gradual reduction in $\langle S_H\rangle$ was observed throughout the remainder of the field range which was studied. From a value of 35 $\mathrm{nT/Hz^{0.5}}$

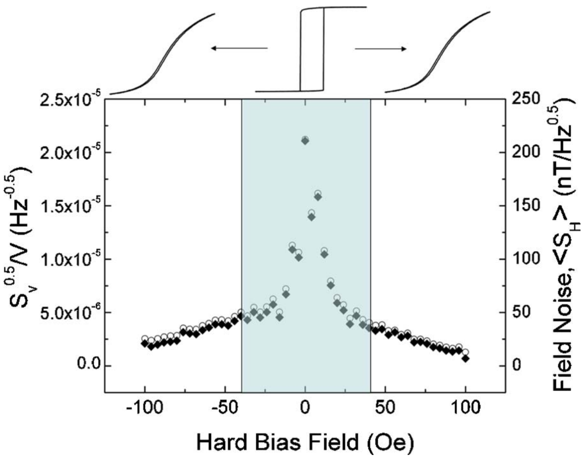

FIG. 3. (Color online) Variation of normalized voltage noise ($\delta V/V$) and average magnetic field noise $\langle S_H \rangle$ measured at 100 Hz, for different hard-axis bias fields. The values are obtained from a linear fit as shown in Fig. 2 and the voltage noise is calculated for $s=1\%/\mathrm{Oe}$. The hysteretic region has been shaded out. A higher hard-axis field bias results in a lower magnetic field noise as indicated by the steady reduction in $\langle S_H \rangle$.

at $H_B=40$ Oe, the magnetic field noise slowly decreases to 17 $\mathrm{nT/Hz^{0.5}}$ at $H_B=80$ Oe, a twofold reduction over 40 Oe. This result is both surprising and important for sensing applications. It implies that the voltage noise can be reduced without significant reduction in the field sensitivity by applying a strong hard-axis bias field. Therefore, a better signal-to-noise ratio can be achieved for a MTJ sensor when such a strong hard-axis bias field is applied. The Dutta-Dimon-Horn model of $1/f$ noise suggests that the observed reduction might indeed be plausible. If the $1/f$ magnetization noise arises from numerous two-level fluctuations, the presence of a strong external field would tend to quench these fluctuations, leading to an energetically favorable low magnetic noise configuration.

In summary, we have presented a low frequency noise analysis of highly sensitive MgO-based MTJs. When the MTJ is in the sensing state configuration, noise of magnetic origin dominates and the overall voltage noise scales linearly with field sensitivity. We also see substantial fluctuations in the noise spectra which indicate that within the FL of the MTJ there exist random magnetic fluctuations which can be attributed to local domain nucleation or annihilation. We have also investigated in detail the role of the external hard bias field on the magnetic field noise. We find conclusively that a strong external hard bias field enhances the magnetic stability of the FL and lowers the magnetic noise of the MTJ.

This work was supported at Brown University by the National Science Foundation Grant No. DMR-0605966 and at Micro Magnetics, Inc. by the National Science Foundation Grant No. DMR-0522160.

[1] S. S. P. Parkin, C. Kaiser, A. Panchula, P. M. Rice, B. Hughes, M. Samant, and S. H. Yang, Nat. Mater. **3**, 862 (2004).
[2] S. Yuasa, T. Nagahama, A. Fukushima, Y. Suzuki, and K. J. Ando, Nat. Mater. **3**, 868 (2004).
[3] W. H. Butler, X.-G. Zhang, T. C. Schulthess, and J. M. MacLaren, Phys. Rev. B **63**, 054416 (2001).
[4] J. Mathon and A. Umerski, Phys. Rev. B **63**, 220403 (2001).
[5] F. N. Hooge, Physica B **83**, 14 (1976).
[6] P. Dutta, P. Dimon, and P. M. Horn, Phys. Rev. Lett. **43**, 646 (1979).
[7] D. Mazumdar, X. Y. Liu, B. D. Schrag, W. Shen, M. Carter, and G. Xiao, J. Appl. Phys. **101**, 09B502 (2007).
[8] S. Ingvarsson, G. Xiao, S. Parkin, W. Gallagher, G. Grinstein, and R. Koch, Phys. Rev. Lett. **85**, 3289 (2000).
[9] C. Ren, X. Liu, B. D. Schrag, and G. Xiao, Phys. Rev. B **69**, 104405 (2004).
[10] W. Shen, D. Mazumdar, X. Zou, X. Liu, B. D. Schrag, and G. Xiao, Appl. Phys. Lett. **88**, 182508 (2005).