Angular Dependence of Low-Frequency Noise in Al_2O_3-Based Magnetic Tunnel Junction Sensors With Conetic Alloy

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We demonstrated the noise performances of Al_2O_3-based magnetic tunnel junction sensors (MTJs) in the low-frequency regimes. Conetic alloy $Ni_{77}Fe_{14}Cu_5Mo_4$ was deposited as both the MTJ pinned layer and free layer because of its superb magnetically soft properties. A rotating magnetic field was employed to investigate the angular dependence of the MTJ low-frequency noise. Hooge parameter was applied for parameterizing the low-frequency noise. The measurement results demonstrate that the Hooge parameters are angular-dependent and they exhibit a linear relation with respect to the angular magnetoresistive susceptibility. It can be also observed that the Hooge parameters possess a higher value when the Conetic MTJs are in the region of antiparallel state. These results indicate that the magnetic fluctuations in the ferromagnetic layers contribute to the low-frequency noise level in Conetic MTJ sensors.

***Index Terms*—Conetic, low-frequency noise, magnetic sensors, magnetic tunnel junction (MTJ).**

I. Introduction

MAGNETIC TUNNEL JUNCTION sensors (MTJs) are under comprehensive studies due to their versatile applications including magnetometers and reading heads in hard disk drives [1], because MTJs hold the superiority of large tunneling magnetoresistance (TMR) ratios. Previous study reported the application of Conetic alloy in the Al_2O_3-MTJ pinned layer and free layer for its magnetically soft properties, and it was demonstrated to effectively reduce the saturation fields which is greatly conducive for the sensitivity of MTJ sensors [2]. The Conetic alloy (NiFeCuMo) belongs to mu-metal family and possesses large magnetic susceptibility of $10^4 - 10^5$ and relative small anisotropy in synthetic antiferromagnet multilayers [3], [4], therefore it is an ideal magnetic material for fabricating low-field MTJ sensors.

However, besides the TMR ratio, the ultimate sensitivity and signal-to-noise ratio (SNR) of MTJ sensors are also determined by their noise performance. Previous study revealed that the sensitivity of MTJ sensors does not have much further improvement when the TMR ratio exceeds beyond 100% [5]. One hurdle for MTJs to achieve 1-picoTesla sensitivity is the intrinsic noise problem. The main noise sources in MTJs are comprised of frequency-independent shot noise and thermal noise, and frequency-dependent $1/f$ noise, among which the $1/f$ noise dominates at low-frequency regime and seriously deteriorates the SNR of MTJ sensors. In order to evaluate the noise behavior at low-frequency regime, the $1/f$ noise is commonly parameterized by Hooge parameter (α) which is defined by

$$\alpha = \frac{A \cdot f \cdot S}{V^2} \tag{1}$$

where A is the MTJ junction area, f is frequency, S is noise power and V is the voltage across the junction [6]. The study of Hooge parameters was mainly focused on their performance in both parallel and antiparallel magnetization states during the transition process of MTJ sensors. Their values exhibit variations depending on resistance-area product [7], [8], biasing voltage [9], [10], and annealing conditions [11], [12] of the MTJ sensors.

We herein used a rotating magnetic field method to investigate the MTJ noise performances. This rotating magnetic field method was previously applied for characterizing the free layer anisotropy, pinned-layer orientation, exchange bias strength [13], and exchange bias direction [14] of MTJs. It was also employed for investigating the low-frequency noise characteristics of MgO-based MTJs [15]. In this work, we applied this technique for characterizing the angular performance of noise behavior of the Al_2O_3-MTJ sensors with Conetic alloy. The relations between the magnetic field orientation and the various MTJ parameters including MTJ resistance, angular magnetoresistance susceptibility, and Hooge parameter were studied and analyzed.

II. Experiment

The MTJ thin films were deposited by dc magnetron sputtering on thermally oxidized silicon substrate under a base pressure of 2×10^{-10} Torr with a structure of 20 Conetic ($Ni_{77}Fe_{14}Cu_5Mo_4$) / 1 $Co_{50}Fe_{50}$ / 1 Al, plasma oxidation, $O_2 = 10^{-3}$ Torr, / 1 $Co_{50}Fe_{50}$ / 2.5 Conetic ($Ni_{77}Fe_{14}Cu_5Mo_4$) / 0.5 $Co_{50}Fe_{50}$ / 10 $Ir_{20}Mn_{80}$ / 7 Ru (units in nm). The Al_2O_3 tunneling barrier was formed by depositing the Al metal and oxidizing it in oxygen plasma. The sample was annealed for 15 min at 200°C. The MTJ junctions were fabricated with a junction size of 20×20 μm^2 after self-aligned photolithography and etching processes. The noise measurement was carried out in a Wheatstone bridge configuration to curtail the dc offset and the effect of thermal drift [16]. The output signal from the bridge circuit was amplified through a low-noise instrumentation voltage amplifier (Femto DLPVA-100-BLN-S) and input to a spectrum analyzer (Stanford Research Systems SR785). In this way, both the noise spectrum and resistance of MTJ sensors can be acquired simultaneously. The details of the noise measurement system were introduced in our previous work [2].

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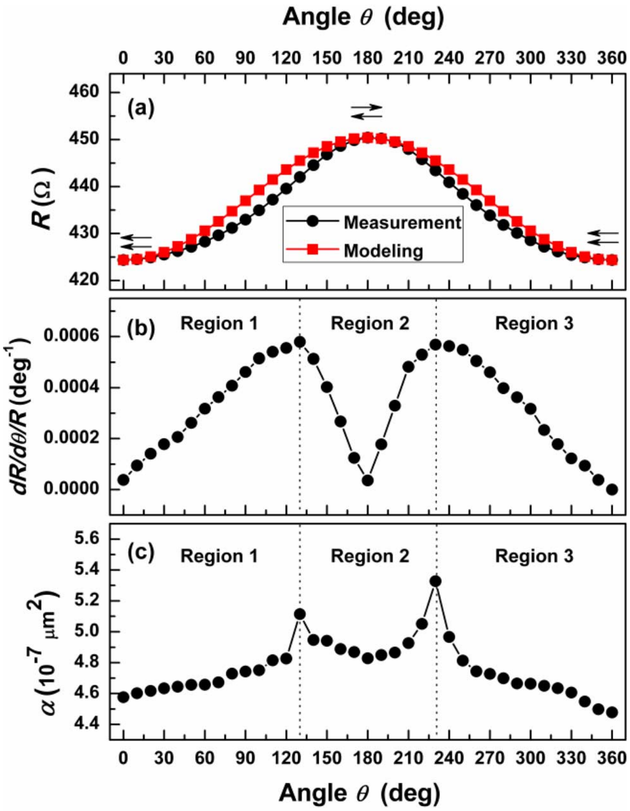

Fig. 1. Relations between the magnetic field orientations and various MTJ parameters. (a) MTJ resistance, the curve with circle symbols are measurement result and the other with square symbols are the simulation result calculated with (2) (the arrows indicate the magnetization directions of MTJ free and pinned layers). (b) Angular MR susceptibility, $dR/d\theta/R$. (c) Hooge parameter, calculated with (1) at the frequency regime of 100 Hz-10 kHz [2]. The vertical dash lines at $\theta = 130^\circ$ and $\theta = 230^\circ$ are the boundaries of the three regions.

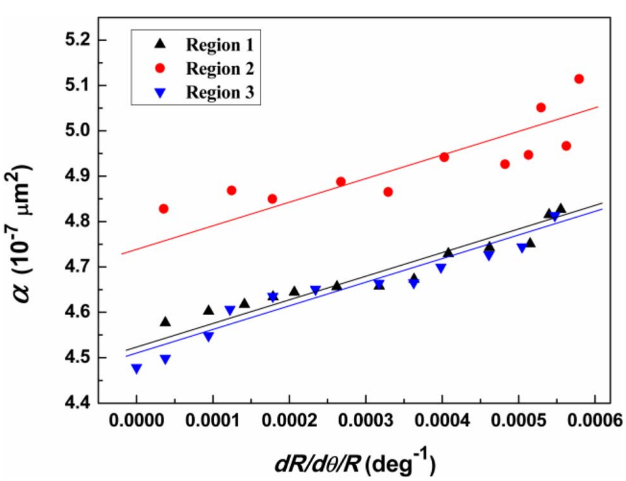

Fig. 2. Hooge parameter α exhibits a linear relation, in the three corresponding regions, with respect to the angular MR susceptibility $dR/d\theta/R$. The solid lines are the linear fitting curves.

The MTJ sensors were powered with a dc biasing current of 50 μA. Two varying magnetic fields were generated by two pairs of Helmholtz coils mounted along the easy-axis and the hard-axis respectively to form vectorially a rotating field with a constant magnitude of 60 Oe which was slightly higher than the MTJ saturation field [2], [17]. This vectorial in-plane biasing field was calibrated by a gaussmeter (LakeShore 455) from 0° to 360° before the measurement. The whole system is shielded in a mu-metal shielding box to avoid the disturbance of ambient magnetic field. All the measurements were performed at room temperature.

III. Result and Discussion

As shown in the curve with solid circle symbols in Fig. 1(a), the resistance of the MTJs was measured as a function of θ, where θ is the angle between the MTJ pinned-layer magnetization and the in-plane rotating-biasing field. The resistance of the MTJ junction increased from minimum at around $\theta = 0^\circ$ and reached maximum at around $\theta = 180^\circ$, and then it returned to minimum at $\theta = 360^\circ$. This indicates the rotating-biasing field can fully alternate the free-layer magnetization from parallel to antiparallel configuration. The result was compared with the modeling equation [18], [19]

$$R(\theta) = \frac{R_P R_{\mathrm{AP}}}{R_P + (R_{\mathrm{AP}} - R_P)\cos^2(\theta/2)} \tag{2}$$

where R_P and R_{AP} are the resistance when the magnetization direction are in parallel and antiparallel state, respectively. The modeling result (curve with solid square symbols in Fig. 1(a)) exhibits the similar behavior as the measured resistance (curve with solid circle symbols). They both show the maximum value when the magnetization directions are antiparallel ($\theta = 180^\circ$) and minimum value when the directions are in parallel state ($\theta = 0^\circ$ and $\theta = 360^\circ$). The slight disagreement between the two curves may result from the orientation difference between the magnetization of the free layer and the reference layer due to the defects in the antiferromagnetic order in the exchange bias [20].

Fig. 1(b) illustrates the relation between angular MR susceptibility against θ. The angular MR susceptibility is the derivative of MR ratios and mathematically expressed by $dR/d\theta/R$ [15]. The maximum values arose at $\theta = 130^\circ$ and $\theta = 230^\circ$. We further explore the relation between the MR susceptibility and the Hooge parameter which was calculated by (1). To simplify the discussion, we separated Fig. 1(b) and (c) into three regions with the boundaries defined at $\theta = 130^\circ$ and $\theta = 230^\circ$ where the MTJ free layer was switching the fastest with respect to the angle θ. As presented in Fig. 1(c), the maximum values of α also exhibit at $\theta = 130^\circ$ and $\theta = 230^\circ$, which is consistent with the result of $dR/d\theta/R$ in Fig. 1(b). The Hooge parameters in Region 1 and Region 3 are smaller than those in Region 2, where the MTJ magnetization directions of the free layer and pinned layer are under antiparallel state. The minima of α exhibit at $\theta = 0^\circ$ and $\theta = 360^\circ$ when the magnetization directions of MTJ pinned layer and free layer are in parallel state, while the maxima of α arise at $\theta = 130^\circ$ and $\theta = 230^\circ$ instead of the antiparallel state (i.e., 180°). This represents that the MTJ sensors possess a higher low-frequency noise level during the transition period of the magnetization orientations of the MTJ pinned layer and the free layer between parallel and antiparallel states. This result on the Al_2O_3-MTJ sensors with Conetic alloy is comparable with other previous studies that used other MTJ sensors or measurement methods [15], [21], [22].

Based on Fig. 1(b) and (c), the relation between the Hooge parameter α and the angular MR susceptibility $dR/d\theta/R$ is plotted in Fig. 2. The α increases linearly with the angular MR susceptibility $dR/d\theta/R$ in all the three corresponding regions. The relation can be described by

$$\alpha = \alpha_0 + k \cdot \left(\frac{1}{R} \cdot \frac{dR}{d\theta}\right) \tag{3}$$

where α_0 is the initial value of Hooge parameter in the corresponding region without angular magnetic field bias and k is the slope of the fitting curves in Fig. 2. The value of α_0 varies in the different regions determined by the magnetization states of the MTJ sensors. The slope k mostly retains a constant value in all the three regions which means k is an intrinsic parameter for the Al_2O_3-MTJ sensors with Conetic alloy. It can also be observed from Fig. 2 that the values of α in Region 2 are higher than those in Region 1 and Region 3, which means α is larger when the MTJs are in the region of antiparallel state. This phenomenon might be attributed to the increased number of domain movement provoked by the antiparallel configuration due to the large magnetic susceptibility and small anisotropy of Conetic alloy. These results indicate that the observed $1/f$ noise is dependent on the derivative of MR ratios. The mechanism of the noise source is provided by the magnetization fluctuations in the MTJ ferromagnetic layers. The fluctuations are most likely originated from, rather than the electron trapping defects nor magnetic impurities in the tunneling barrier which would induce the shot noise and the random telegraph noise, the thermally activated hopping of domain walls between the MTJ pinned layer and free layer. These results are consistent with previously reported work on low-frequency noise in MTJs [15], [21], [23].

IV. Conclusion

The angular dependence of low-frequency noise in the Al_2O_3-MTJ sensors with Conetic alloy was characterized with a rotating magnetic field method. In these Conetic MTJ sensors, the Hooge parameter varies with respect to the angle between the MTJ pinned-layer magnetization and the in-plane rotating-biasing field. It was observed that, in the corresponding regions, the Hooge parameters hold a linear relation with the derivative of MR ratios. Due to the high magnetic susceptibility, the Conetic MTJ sensors exhibit a larger low-frequency noise when they are in the region of antiparallel state compared to when the Conetic MTJ sensors are in parallel state. This indicates that the magnetization fluctuations in the ferromagnetic layer contribute to the low-frequency noise, and the Conetic MTJ sensors exhibit similar behavior as the other MTJ sensors in this regard.

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