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Field sensing in MgO double barrier magnetic tunnel junctions with a superparamagnetic $Co_{50}Fe_{50}$ free layer

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Linear response and low frequency noise have been investigated in MgO double barrier magnetic tunnel junctions with a superparamagnetic $Co_{50}Fe_{50}$ free layer. Linear and hysteresis-free switching was observed for the $Co_{50}Fe_{50}$ thickness $t \leq 1$ nm. A tunneling magnetoresistance ratio of up to 108% and large magnetic field sensitivity value of 61%/mT were obtained at room temperature when $t = 1.0$ nm. The angular dependence of magnetoresistance suggests that weak coupling between superparamagnetic islands in a 1.0 nm free layer permits continuous rotation of magnetization, whereas the islands in a 0.8 nm layer switch rather independently. The frequency dependence of noise power spectrum density and field dependence of Hooge parameter (α) also behave differently for junctions with 0.8 and 1.0 nm free layers. The noise sensitivity of 1.0 nm free layer junctions is independent of bias, and it is estimated to reach 400 $pT/Hz^{0.5}$ at 500 kHz. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4723836]

INTRODUCTION

Magnetic tunnel junctions (MTJs) with crystalline MgO barriers have been extensively studied due to their high tunneling magnetoresistance (TMR) and potential for applications in spin torque driven magnetic random access memories (ST-MRAMs) and field sensors.[1–4] A record TMR ratio of 604% at room temperature and 1144% at 5 K, approaching the theoretically predicted values,[5,6] has been reported in MTJs with a pseudo spin valve stack.[7] In spin-valve based magnetic field sensors, a linear response is usually obtained through the crossed magnetic alignment of the free and pinned layers, which can be obtained by shape anisotropy, exchange bias or specifically induced external field.[8–10] Recently, several groups proposed that a discontinuous ferromagnetic free layer can induce a linear response in MgO single barrier (SB-) or double barrier (DB-) MTJs.[11–14] When the free layer thickness is below a critical value, it breaks up into nanoislands on the MgO surface, which are superparamagnetic.[11–15] Realizing a linear response in DB-MTJs, which have better bias dependence of TMR compared to SB-MTJs,[16–18] is advantageous for sensor applications.

In addition to the linear response, a low noise level is necessary for sensor applications. In the low-frequency regime, the noise is usually dominated by $1/f$ noise. The performance of the MTJ sensor with $1/f$ noise can be described by the noise parameter $S_V(T/Hz^{0.5})$:[19]

$$S_V(T/Hz^{0.5}) = \frac{\Delta H}{TMR(V)}\sqrt{\frac{\alpha}{Af}}, \qquad (1)$$

where α is the Hooge parameter, ΔH is the linear field range, V is the applied voltage, TMR (V) is the bias-dependent TMR ratio, A is the junction area, and f is the frequency. To achieve a low value of S_V, which corresponds to a high sensitivity for sensor devices, both high TMR and low α are needed.

In this work, we investigate the linear response and low frequency noise in MgO DB-MTJs with a thin $Co_{50}Fe_{50}$ (CoFe) middle free layer of thickness $t = 0.8$, 1.0, and 1.2 nm. The layers with $t \leq 1.0$ are superparamagnetic at room temperature. The field dependence of TMR at angles of 0° - 90° shows that DB-MTJs with 1.2 nm and 1.0 nm CoFe have similar behavior to SB-MTJs with a thick free layer. But they differ from DB-MTJs with a 0.8 nm CoFe free layer. Low frequency noise has been measured in the linear response field regime. $1/f$ noise is observed for 1.0 nm DB-MTJs, while the noise spectrum deviates from $1/f$ noise for 0.8 nm DB-MTJs. Also the field dependence of noise is different. These differences are discussed.

EXPERIMENT

DB-MTJ stacks were grown on thermally oxidized silicon wafers with a layer sequence Ta (5)/Ru (30)/Ta (5)/$Ni_{81}Fe_{19}$ (5)/$Ir_{22}Mn_{78}$ (10)/$Co_{90}Fe_{10}$ (2.5)/Ru (0.9)/$Co_{40}Fe_{40}B_{20}$ (CoFeB) (3)/MgO (2.5)/$Co_{50}Fe_{50}$ (t)/MgO (2.5)/CoFeB (3)/Ru (0.9)/$Co_{90}Fe_{10}$ (2.5)/$Ir_{22}Mn_{78}$ (10)/$Ni_{81}Fe_{19}$ (5)/Ta (5)/Ru (5). A SB-MTJ stack with a layer sequence Ta (5)/Ru (30)/Ta (5)/$Ni_{81}Fe_{19}$ (5)/$Ir_{22}Mn_{78}$ (10)/$Co_{90}Fe_{10}$ (2.5)/Ru (0.9)/CoFeB (3)/MgO (2.5)/CoFeB (3)/Ta (5)/Ru (5) (thicknesses in nm) was also grown as a comparison. Metallic layers were dc-magnetron sputtered, whereas MgO was rf-sputtered from a facing target source. All layers were grown at ambient temperature in high vacuum using a Shamrock cluster deposition tool. We grew DB-MTJs with the CoFe thickness t of 0.8, 1.0, or 1.2 nm. MTJ stacks were patterned into 10 × 10, 10 × 30, 20 × 20, 20 × 60, 50 × 50, and 50 × 150 μm^2 junctions using conventional UV lithography and argon ion milling. The

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samples were then annealed in high vacuum for 1 h in an in-plane magnetic field of 0.8 T. Magnetotransport and noise measurements were performed at room temperature using the conventional four-point method.[20–22]

RESULTS AND DISCUSSION

Figure 1 shows the room temperature TMR curves of SB- and DB-MTJs with different middle free layer thickness. First, we discuss the TMR curves changing with the field applied parallel to the exchange bias direction of the pinned layer(0 degree). The TMR ratio of SB-MTJs with a 3 nm CoFeB free layer reaches 296%, as shown in Fig. 1(a), which reflects the high quality of the MgO barriers. TMR in DB-MTJs with $t = 1.2$ nm is 137%, and it decreases to 39% in junctions with $t = 0.8$ nm. The TMR ratio of 108% for DB-MTJs with $t = 1$ nm is higher than that for DB-MTJs with a superparamagnetic CoFeB free layer.[12] The high TMR is due to the well-oriented CoFe (001) free layer rather than amorphous CoFeB which cannot crystallize during annealing due to the blocking of boron diffusion by the MgO barriers in DB-MTJ stacks.[18,23] The magnetoresistance curve displays a two-step switching due to the different exchange bias fields of top and bottom pinned layers in 1.2 nm DB-MTJ samples, which is unique to DB-MTJs' characteristics.[17] The contribution of the top MTJ to the effective TMR is around 13% for the 1.2 nm free layer. However, two-step switching cannot be observed once the middle free layer enters the superparamagnetism region. For example, only single step switching occurs for 1.0 nm free layer, while no switching is seen in 0.8 nm samples. This suggests that the contribution of the top MTJ to the effective TMR gets smaller. It is probably due to the broad reversal area for the discontinuous free layer, which may be improved by enhancing the exchange bias of the top pinned layer. Figures 2(a)–2(c) show the minor loops of the TMR of DB-MTJs with $t = 1.2$, 1, and 0.8 nm, respectively. For $t = 1.0$ nm, a magnetic field sensitivity of up to 61%/mT is obtained in the field range from −1.9 to −2.7 mT. The magnetic field sensitivity decreases to 0.26%/mT when $t = 0.8$ nm, but the linear field range extends from −40 to 12.5 mT. For sensor applications, the magnetic field sensitivity must be balanced against the linear response field range.

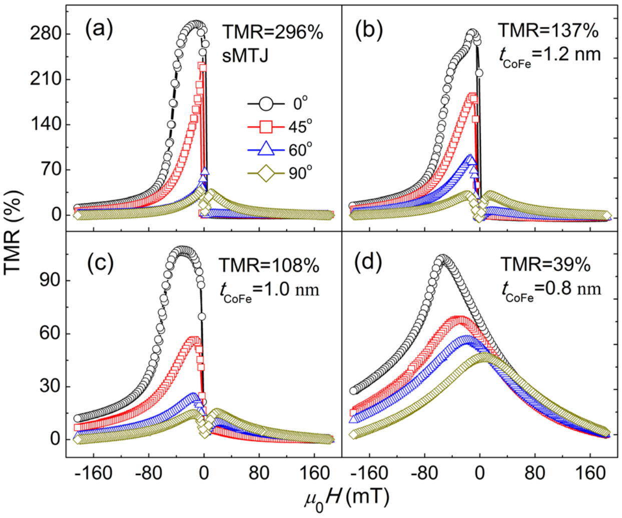

FIG. 1. Resistance vs magnetic field for an SB-MTJ (a) and three DB-MTJs with free layer thickness 1.2 nm (b), 1 nm (c), and 0.8 nm (d). Magnetic field is applied at various in-plane angles to the pinned layer.

We analyzed the transfer curve of $t = 1.0$ nm, using the theory of superparamagnetism:[14]

$$\Delta G = G - G_0 \propto \cos\theta_F \propto M_F,$$

where magnetization component (M_F) follows a Langevin equation. The thickness of free layer is considered to be 1.0 nm, and the saturation magnetization is $M_s = 1.9 \times 10^6$ A/m.[24] By fitting the curve, the lateral dimensions of the superparamagnetic particles are deduced to be 90–94 nm, where the particles are considered to have a pancake shape. The fitting is good enough with adjusted r-square value >0.995. Referring to the phase diagram in Ref. 25 and the results in Ref. 24, where $Co_{50}Fe_{50}$ dots with size of 335 nm by 225 nm and thickness of 10 nm are single domain, it is suggested that the superparamagnetic particles in the free layer of $t = 1.0$ nm are mostly single domain. Therefore, it is expected that the 0.8 nm free layer should be comprised of single-domain particles with smaller size compared with the 1.0 nm free layer.

Magnetic transport measurements were carried out at different angles (θ) between the applied magnetic field and the magnetic easy axis of the free layer. TMR curves of DB-MTJs with 1.0 and 1.2 nm CoFe for $0 \le \theta \le 90°$ are similar to those of SB-MTJs with a 3 nm free layer, as shown in Figs. 1(a)–1(c). There are two humps at positive and negative fields when the magnetic field is not parallel to the easy axis (60°-90°). However, TMR curves for DB-MTJs with $t = 0.8$ nm are different [Fig. 1(d)]. The superparamagnetic particles may be well isolated in the 0.8 nm CoFe film, which

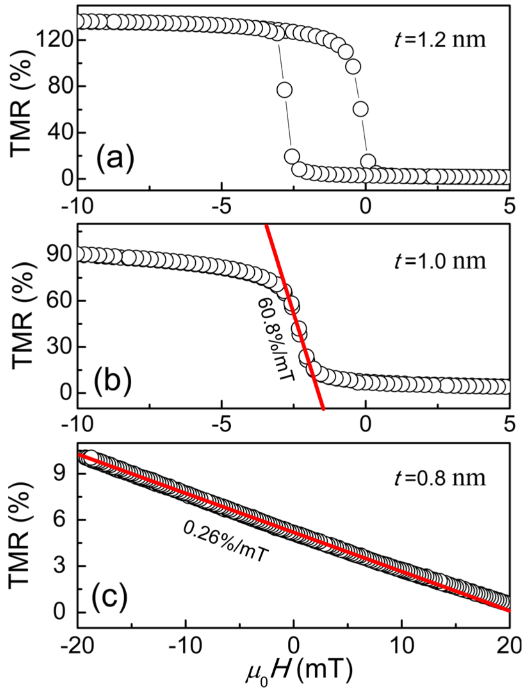

FIG. 2. Minor loops of DB-MTJs with free layer thickness 1.2 nm (a), 1 nm (b), and 0.8 nm (c). Red lines show the linear field range. The field angle is 0 degree.

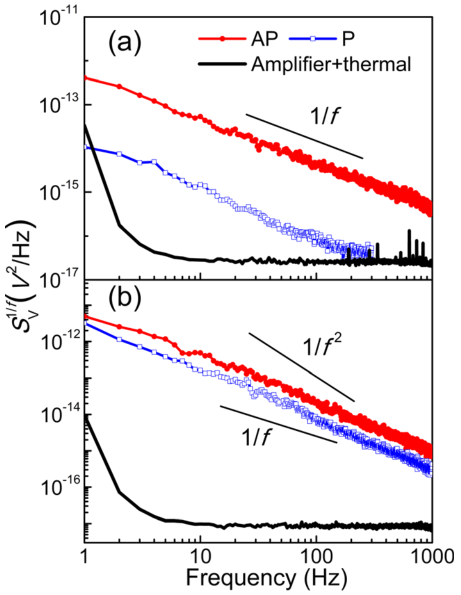

FIG. 3. Noise power spectrum density as a function of frequency in AP (−20 mT) and P (60 mT) states for DB-MTJ samples with $t = 1$ nm (a) and 0.8 nm (b), after subtracting the thermal and amplifier noise. The junction sizes are 20×60 mm^2 and 10×30 mm^2 for 1 nm and 0.8 nm junctions, respectively.

reverse their direction of magnetization independently. On the other hand, the weak coupling between the islands in the 1.0 nm film leads them to switch like a continuous thin film.

Figure 3 presents the noise power spectrum $S_V^{1/f}$ (V^2/Hz) as a function of frequency up to 1 kHz for DB-MTJs with $t = 1$ and 0.8 nm. $S_V^{1/f}$ is found to scale approximately V^2/f^{β}, after the thermal and amplifier noise have been subtracted. Usually, we use Hooge parameter α to characterize the noise level, which is defined as

$$\alpha = A f^{\beta} S_V^{1/f}/V^2, \tag{2}$$

where β is the exponent of the noise spectrum which specifies the exact frequency dependence. No random telegraph noise is observed for DB-MTJs with $t = 1$ or 0.8 nm. For the 1.0 nm case, the 1/*f*-like noise dominates in both parallel (P) ($\beta = 0.930 \pm 0.016$) and antiparallel (AP) ($\beta = 0.958 \pm 0.003$) states. However, the noise deviates from 1/*f* noise in both P ($\beta = 1.326 \pm 0.003$) and AP ($\beta = 1.306 \pm 0.007$) states for the 0.8 nm DB-MTJ samples, which may be due to irreversible Barkhausen jumps and magnetization drift.[22]

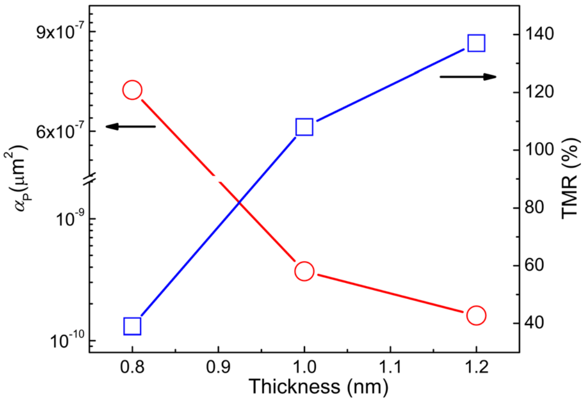

FIG. 4. Thickness dependence of TMR and α_P.

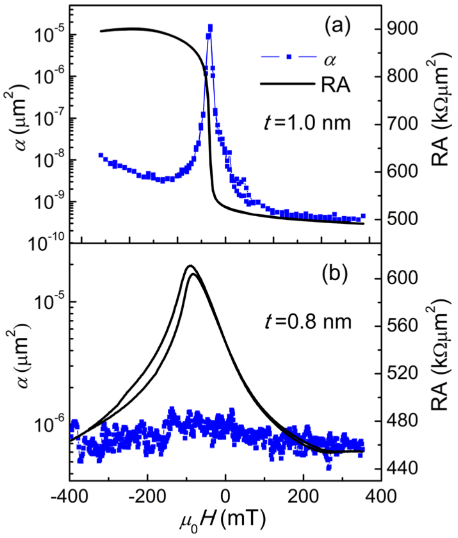

FIG. 5. Magnetic field dependence of Hooge parameter (α) and RA for DB-MTJs with $t = 1$ nm (a) and 0.8 nm (b).

Figure 4 shows the thickness dependence of α in the P state (α_P). For the 1.2 and 1.0 nm free layers, α_P is around 3.1×10^{-10} μm^2, which is in the same range to that in SB-MTJs with a thick free layer.[26,27] The noise in the P state is believed to be dominated by barrier noise, which is attributed to defects in the MgO barriers and at the MgO/CoFe and CoFeB/MgO interfaces.[20] α_P increases and TMR decreases on decreasing the thickness of the free layer. For the 0.8 nm case, the α_P value increases to 7.1×10^{-7} μm^2, at least three orders of magnitude higher compared to that for the 1.0 nm junctions. This suggests that isolated superparamagnetic particles in the barrier can lead to a higher noise level compared to weakly coupled particles. This could be due to the thermally activated magnetization fluctuations of the nanoparticles, which is thought to be the origin of the noise.[21,28] For the 1.0 nm free layer, weak magnetic coupling among the superparamagnetic islands may suppress the thermally activated magnetization fluctuations in the parallel state. However, in the linear

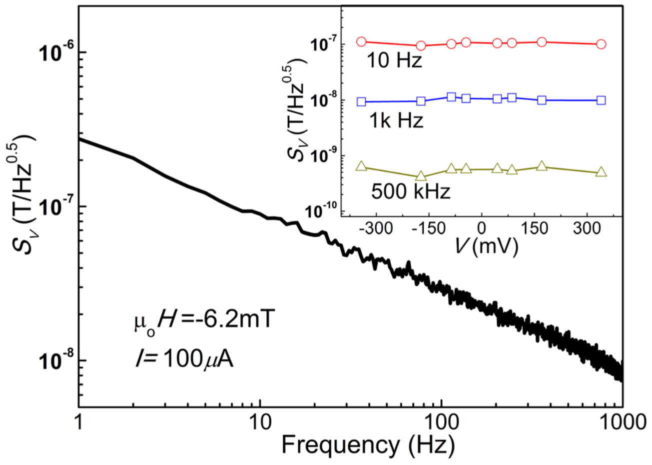

FIG. 6. Field detection capability for DB-MTJ with 1 nm free layer. Inset: The bias dependence of field detection capability at 10 Hz, 1 kHz, and 500 kHz, respectively.

response region, α changes dramatically by four orders of magnitude as a function of field for the 1.0 nm junctions, as shown in Fig. 5. The magnetization fluctuation is enhanced in the reversal process of the free layer.

Finally, we estimate the noise parameter S_V(T/Hz$^{0.5}$) in DB-MTJs with 1.0 nm CoFe, which is measured at $\mu_0 H = -6.2$ mT where the field sensitivity is the greatest. It also follows the 1/*f*-like dependence ($\beta = 0.979 \pm 0.002$), as shown in Fig. 6. Using Eq. (1), the S_V at 10 Hz is 90 nT/Hz$^{0.5}$, and it decreases to 10 nT/Hz$^{0.5}$ at 1 kHz. Extrapolating to 500 kHz, S_V reaches 400 pT/Hz$^{0.5}$. Furthermore, S_V was also measured at different bias (Fig. 6 inset). We find that S_V in 1.0 nm DB-MTJs is almost bias independent (−350 mV-+350 mV), contrary to the findings of Almeida *et al.*[12]

CONCLUSION

In conclusion, a linear and hysteresis-free response has been observed in MgO DB-MTJs with a superparamagnetic CoFe free layer ($\leq$1.0 nm). A high TMR of 108% and large magnetic field sensitivity value of 61%/mT are obtained for DB-MTJs with a 1.0 nm CoFe free layer. The magnetotransport properties and the low frequency noise behave differently for DB-MTJs with 0.8 and 1.0 nm free layers. It is suggested that well isolated CoFe nanoislands in the free layer can lead a higher noise level compared to weakly coupled nanoparticles due to the thermally activated magnetization fluctuations of nanoparticles. The noise parameter S_V as low as 400 pT/Hz$^{0.5}$ is expected at 500 kHz, and it is almost bias independent. These DB-MTJs could be potentially useful for magnetic sensor devices with high signal to noise ratios.

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