Thermal-magnetic noise measurement of spin-torque effects on ferromagnetic resonance in MgO-based magnetic tunnel junctions

Y. Guan* and J. Z. Sun

IBM T. J. Watson Research Center,
Yorktown Heights, New York 10598, USA

X. Jiang, R. Moriya, L. Gao, and S. S. P. Parkin

IBM Almaden Research Center, San Jose, California 95120, USA

(Dated: August 15, 2009)

Abstract

Thermal-magnetic noise at ferromagnetic resonance (T-FMR) can be used to measure magnetic perpendicular anisotropy of nanoscale magnetic tunnel junctions (MTJs). For this purpose, T-FMR measurements were conducted with an external magnetic field up to 14 kOe applied perpendicular to the film surface of MgO-based MTJs under a dc bias. The observed frequency-field relationship suggests that a 20 Å CoFeB free layer has an effective demagnetization field much smaller than the intrinsic bulk value of CoFeB, with $4\pi M_{\text{eff}} = (6.1 \pm 0.3)$ kOe. This value is consistent with the saturation field obtained from magnetometry measurements on extended films of the same CoFeB thickness. In-plane T-FMR on the other hand shows less consistent results for the effective demagnetization field, presumably due to excitations of more complex modes. These experiments suggest that the perpendicular T-FMR is preferred for quantitative magnetic characterization of nanoscale MTJs.

* The author is currently with SoloPower Inc., 5981 Optical Court, San Jose, California 95138. Electronic mail: yguan@solopower.com.
Understanding and controlling magnetic properties of thin layers in a spatially confined magnetic system are of growing interest for fundamental physics studies and for spin-torque-based magnetic memory and microwave oscillator applications\cite{1, 2, 3, 4, 5}. Specifically, the layer magnetic anisotropy, damping, and effective magnetization, are of particular importance for the performance of spin-torque-based devices\cite{6}. Although conventional ferromagnetic resonance (FMR) detection methods lack the sensitivity to measure individual nanoscale structures, thermal-magnetic noise measurement of ferromagnetic resonance (T-FMR) enables direct studies of magnetic properties of patterned nanoscale devices\cite{7, 8, 9, 10, 11, 12}.

For a dc-biased nanoscale magnetic device below its spin-torque-induced magnetic instability, the system is essentially driven by thermal noise. By monitoring high-frequency thermal magnetization fluctuations of the device, field- and bias-dependent T-FMR spectra can be obtained. Thermal fluctuations play a significant role in determining spin-torque-driven magnetic switching in nanoscale magnetic tunnel junctions (MTJs)\cite{13}. Therefore, T-FMR could also be useful for further understanding spin-torque dynamics in MTJs.

In this letter, we present room-temperature T-FMR studies of MgO-based nanopillar MTJs between 2 and 8 GHz, where an external magnetic field up to 14 kOe is applied perpendicular to the film surface of the subcritically dc-biased MTJs. The observed perpendicular field dependence of the T-FMR frequency is consistent with Kittel formula. The effective demagnetization field of the CoFeB free layer has been determined, which is compared with those obtained on extended films of the same CoFeB thickness.

The nanopillar MTJs have a stack structure of Si/SiO$_2$/Ta(75)/Cu(200)/Ta(50)/IrMn(120)/CoFeB(6)/CoFe(30)/Ru(7)/CoFe(27)/MgO(10)/CoFeB(20)/Ta(50)/Ru(50), where the numbers are layer thickness in angstroms, CoFe = Co$_{70}$Fe$_{30}$, and CoFeB = Co$_{40}$Fe$_{40}$B$_{20}$. Nanopillars were patterned down to about 100 nm using electron beam lithography. The main results presented here are from a representative 50 × 140 nm$^2$ MTJ with a barrier resistance-area product (RA) of $\sim$11 Ω $\mu$m$^2$ and a tunneling magnetoresistance ratio (TMR) of $\sim$110%. The MTJ was fully patterned through the pinned layer, stopping at the bottom IrMn.

A simplified diagram of the T-FMR experimental setup is shown in Fig. 1(a), where a 50 Ω bias-T is used for simultaneous dc and microwave signal coupling into and out of
the MTJ. The dc bias current ($I$) is defined positive when current flows from the top free layer (FL) to the bottom pinned layer (PL). The output T-FMR signals are fed into a 35 dB low-noise amplifier and then into a spectrum analyzer. The resolution bandwidth of the spectrum analyzer is set to 5 MHz. Each spectrum is obtained by averaging over 100 spectral scans. A more detailed description about the T-FMR experimental setup can be found in our previous report [12].

Perpendicular T-FMR measurements are performed at room temperature with an external magnetic field up to 14 kOe applied perpendicular to the film surface of the subcritically dc-biased MTJ up to 360 µA. Figure 1(b) shows the tunnel resistance ($R$) of the MTJ as a function of the applied perpendicular magnetic field ($H$) for a small dc bias of $I = 1$ µA. The cusp in Fig. 1(b) corresponds fairly closely to the CoFeB free-layer’s perpendicular saturation field reflecting the easy-plane anisotropy.

Figure 2(a) shows typical perpendicular T-FMR spectra of the MTJ measured at various applied magnetic fields for the same dc bias of $I = 360$ µA. For all data presented, a zero bias spectrum is subtracted, which removes the background Johnson noise as well as the amplifier noise. As shown in Fig. 2(a), the T-FMR peaks decrease in amplitude and shift to higher frequencies with increasing applied magnetic field.

The perpendicular field dependence of the T-FMR frequency for the MTJ for $I = -360$ µA is presented in Fig. 2(b), where the peak frequency ($f$) is extracted with a single Lorentzian fit. The data are well fitted using the perpendicular field Kittel formula [14]

$$f = \frac{\gamma}{2\pi} (H_{res} - 4\pi M_{eff}),$$  

(1)

where $\gamma = g\mu_B/\hbar$ is the gyromagnetic ratio, $g$ is the Landé factor, and $\mu_B$ is the Bohr magneton. $H_{res}$ denotes the T-FMR resonance field, and $M_{eff}$ denotes the effective demagnetization. In fitting the data, we treat $g$ and $M_{eff}$ as free parameters. The best fit gives $4\pi M_{eff} = (6.1 \pm 0.3)$ kOe and $g = 2.0 \pm 0.1$ for the 20 Å CoFeB free layer of the MTJ. Variations of $\sim 5\%$ in $M_{eff}$ and $\sim 10\%$ in $g$ were observed between dc bias of -360 and 360 µA. In addition, $f$ increases with increasing negative dc bias and exhibits smaller change at positive dc bias for all the measured values of $H$. This bias-dependent asymmetry in the T-FMR frequency shift has also been observed on other MTJs by spin-torque-driven FMR [15, 16]. However, the mechanisms behind it are still unclear so far.
The $4\pi M_{\text{eff}}$ value thus obtained for the 20 Å CoFeB free layer of the MTJ is much smaller than the saturation moment ($4\pi M_s$) of bulk CoFeB. This characteristic is similar to previous reports\[8, 9, 10\]. For comparison, out-of-plane moments of extended films with a stack structure of MgO(30)/CoFeB($t$)/Ta(20)/Ru(20) were measured using a SQUID magnetometer, where the numbers are layer thickness in angstroms, CoFeB = Co$_{40}$Fe$_{40}$B$_{20}$, and $t = 20$ and 100. Before the SQUID measurements, these extended films were annealed at 300°C with an in-plane magnetic field of 10 kOe, a treatment similar to the real stack used for tunnel junction devices. Figure 3(a) shows the magnetic moment ($4\pi M$) of the extended CoFeB films as a function of the applied out-of-plane magnetic field ($H$) for both the thicknesses of 20 and 100 Å. The saturation moment ($4\pi M_s$) of the CoFeB is determined to be $\sim 15$ kOe for $t = 100$ and $\sim 12$ kOe for $t = 20$. In addition, the saturation field of the CoFeB is found to be $\sim 6$ kOe for $t = 20$, much smaller than the $4\pi M_s$ value but in reasonable agreement with the $4\pi M_{\text{eff}}$ value determined from the perpendicular T-FMR measurements. The origin of the discrepancy between the measured saturation moment and the saturation field is not entirely clear. On one hand, the magnetic granularity of the thin film over a length-scale comparable to film thickness could result in such reduction of the saturation field. On the other hand, the possible presence of an interface-mediated perpendicular magnetic anisotropy could also reduce the apparent saturation field. Which of these two mechanisms is responsible for these observations is not yet unambiguously determined. It should also be noted that a reduced saturation field is expected in finite size elements due to the exchange and dipolar contributions to the resonance frequencies\[17, 18\]. However, since the reference-layer/free-layer (RL/FL) in the MTJ is nearly compensated and has a thinner total magnetic thickness, the low-field dipolar correction from the RL/FL in our case is expected to be much smaller than those discussed for a spin-valve junction with an uncompensated and much thicker RL/FL\[18\].

We finally compare the perpendicular T-FMR measurements with the in-plane T-FMR measurements on the same MTJ. With an in-plane magnetic field up to 2.5 kOe applied along the hard axis of the CoFeB free layer, the in-plane T-FMR were measured for various dc bias up to 270 µA. Figure 3(b) plots the in-plane hard-axis field dependence of the T-FMR frequency for $I = 270$ µA. The data are fitted using the Kittel formula for in-plane
hard-axis field $f = \frac{\gamma}{2\pi} \sqrt{(H_{\text{eff}} - H_k)(H_{\text{eff}} + 4\pi M_{\text{eff}})}$, (2)

where $H_k$ is the in-plane uniaxial anisotropy field. $H_{\text{eff}} = H + H_{\text{coupling}} + Dk^2/g\mu_B$, where $H_{\text{coupling}}$ denotes the effective coupling field between the free layer and the pinned layer, $D$ is the exchange stiffness, and $k$ is the spin-wave wave vector. In fitting the data, we take $g = 2.0$, neglect the $H_{\text{coupling}}$ term, and consider only $k = 0$ modes with $H_k$ and $M_{\text{eff}}$ treated as free parameters. The best fit gives a $4\pi M_{\text{eff}}$ value of $(1.1 \pm 0.3)$ kOe, and a variation of $\sim 10\%$ in $M_{\text{eff}}$ was observed between dc bias of -270 and 270 $\mu$A. The effective demagnetization field obtained from the in-plane T-FMR measurements is significantly smaller than those determined from the perpendicular T-FMR and the out-of-plane SQUID measurements. This could be due to the possible involvement of nonmacropin modes in thermally excited magnetization fluctuations, specifically the plausible presence of magnetic edge modes $^{19, 20}$. Such modes could make the quantitative determination of saturation moment and magnetic anisotropy energy difficult from in-plane T-FMR data.

In summary, we have found that the perpendicular field dependence of the T-FMR frequency is in good agreement with Kittel formula. The extracted effective demagnetization field of the 20 Å CoFeB free layer is smaller than the intrinsic bulk value of CoFeB, but in accord with the saturation field value determined from the out-of-plane magnetometry measurements on extended films of the same CoFeB thickness. Our results suggest that the perpendicular T-FMR is more suitable for quantitative characterization of the magnetic parameters of nanoscale MTJs.

We wish to thank the valuable input and support from the MRAM team at IBM T. J. Watson Research Center. This work also benefited from an MRAM development alliance program between IBM and MagIC.

[1] J. C. Sankey, P. M. Braganca, A. G. F. Garcia, I. N. Krivorotov, B. A. Buhrman, and D. C. Ralph, Phys. Rev. Lett. 96, 227601 (2006).
[2] G. D. Fuchs, J. C. Sankey, V. S. Pribiag, L. Qian, P. M. Braganca, A. G. F. Garcia, E. M. Ryan, Zhi-Pan Li, O. Ozatay, D. C. Ralph, and R. A. Buhrman, Appl. Phys. Lett. 91, 062507 (2007).
[3] W. Chen, J.-M. L. Beaujour, G. de Loubeans, A. D. Kent, and J. Z. Sun, Appl. Phys. Lett. 92, 012507 (2008).

[4] D. Houssameddine, S. H. Florez, J. A. Katine, J.-P. Michel, U. Ebels, D. Mauri, O. Ozatay, B. Delaet, B. Viala, L. Folks, B. D. Terris, and M.-C. Cyrille, Appl. Phys. Lett. 93, 022505 (2008).

[5] A. M. Deac, A. Fukushima, H. Kubota, H. Machara, Y. Suzuki, Y. Nagamine, K. Tsunekawa, D. D. Djayaprawira, and N. Watanabe, Nat. Phys. 4, 803 (2008).

[6] J. Z. Sun, Phys. Rev. B 62, 570 (2000).

[7] A. V. Nazarov, H. S. Cho, J. Nowak, S. Stokes, and N. Tabat, Appl. Phys. Lett. 81, 4559 (2002).

[8] V. Synogatch, N. Smith, and J. R. Childress, J. Appl. Phys. 93, 8570 (2003).

[9] N. Stutzke, S. L. Burkett, and S. E. Russek, Appl. Phys. Lett. 82, 91 (2003).

[10] S. Petit, C. Baraduc, C. Thirion, U. Ebels, Y. Liu, M. Li, P. Wang, and B. Dieny, Phys. Rev. Lett. 98, 077203 (2007).

[11] S. Petit, N. de Mestier, C. Baraduc, C. Thirion, Y. Liu, M. Li, P. Wang, and B. Dieny, Phys. Rev. B 78, 184420 (2008).

[12] Y. Guan, D. W. Abraham, M. C. Gaidis, G. Hu, E. J. O’Sullivan, J. J. Nowak, P. L. Trouilloud, D. C. Wорledge, and J. Z. Sun, J. Appl. Phys. 105, 07D127 (2009).

[13] T. Devolder, J. Hayakawa, K. Ito, H. Takahashi, S. Ikeda, P. Crozat, N. Zerounian, J.-V. Kim, C. Chappert, and H. Ohno, Phys. Rev. Lett. 100, 057206 (2008).

[14] C. Kittel, *Introduction to Solid State Physics* (Wiley, New York, 2005).

[15] H. Kubota, A. Fukushima, K. Yakushiji, T. Nagahama, S. Yuasa, K. Ando, H. Maehara, Y. Nagamine, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe, and Y. Suzuki, Nat. Phys. 4, 37 (2008).

[16] J. C. Sankey, Y.-T. Cui, J. Z. Sun, J. C. Slonczewski, R. A. Buhrman, and D. C. Ralph, Nat. Phys. 4, 67 (2008).

[17] B. A. Kalinikos and A. N. Slavin, J. Phys. C 19, 7013 (1986).

[18] W. Chen, G. de Loubens, J.-M. L. Beaujour, A. D. Kent, and J. Z. Sun, J. Appl. Phys. 103, 07A502 (2008).

[19] R. D. McMichael and B. B. Maranville, Phys. Rev. B 74, 024424 (2006).
FIG. 1: (Color online) (a) A simplified diagram of the T-FMR experimental setup. (b) Perpendicular field dependence of the tunnel resistance of the MTJ for $I = 1 \mu$A.
FIG. 2: (Color online) (a) Typical perpendicular T-FMR spectra of the MTJ measured at various applied magnetic fields for $I = 360 \mu A$. (b) Perpendicular field dependence of the T-FMR frequency for the MTJ for $I = -360 \mu A$, including fits to Eq. (1).
FIG. 3: (Color online) (a) Out-of-plane SQUID measurements of the magnetic moment of the extended CoFeB films as a function of the applied magnetic field for both the thicknesses of 20 and 100 Å. (b) In-plane hard-axis field dependence of the T-FMR frequency for the MTJ for $I = -270 \mu\text{A}$, including fits to Eq. (2).