Perpendicular Spin Torque in Magnetic Tunnel Junctions

O. G. Heinonen,* S. W. Stokes, and J. Y. Yi

Recording Heads Operation, Seagate Technology, 7801 Computer Ave, Bloomington, Minnesota 55435, USA

(Received 23 April 2010; revised manuscript received 23 June 2010; published 6 August 2010)

A steady-state electrical current flowing in a magnetic heterostructure can exert a torque on the magnetization, and provides a means to control magnetization states and dynamics in spintronics structures. However, some components of the torque are difficult to measure and to calculate. We have determined the perpendicular spin torque in MgO magnetic tunnel junctions by measuring their lowest ferromagnetic resonance frequency and find that it decreases linearly with increasing bias voltage. Micromagnetic modeling shows that this decrease is caused by the perpendicular component of spin torque. We obtain a quantitative value for the perpendicular spin torque effective field as a function of bias voltage, and show that this effective field is a linear function in bias voltage and approximately equal in magnitude to the in-plane spin torque effective field.

DOI: 10.1103/PhysRevLett.105.066602 PACS numbers: 72.25.Rb, 75.60.Jk, 85.75.Dd

The prediction by Slonczewski [1] and Berger [2] that a spin-polarized current can exert a magnetic torque on layers with noncollinear magnetization has led to intense research over the past decade. This spin torque leads to a direct coupling between transport and local magnetization. As a consequence, steady-state currents can affect the magnetization dynamics, and magnetization dynamics can induce steady-state currents. The coupling between transport and magnetization is of fundamental interest as it provides a means to control magnetization states and dynamics in spintronics structures. Most observations of effects induced by spin torque have been in magnetic multilayer structures. Typically, these contain a ferromagnetic layer with fixed magnetization direction, and a ferromagnetic layer, the free layer (FL), the magnetization direction of which is manipulated and detected. These layers are separated by a nonmagnetic spacer such as Cu, aluminum oxide, or MgO. When the spacer is insulating, the structure is referred to as a magnetic tunnel junction (MTJ). At large enough applied current densities, spin torque can induce coherent oscillations, chaotic magnetization dynamics, or switching of the magnetization direction of the FL [3–6]. Zhang, Levy, and Fert [7] pointed out that the spin torque has not only the in-plane component predicted by Slonczewski [1] and Berger [2], but also a perpendicular component. This latter component is small in metallic systems [8–10] but much larger in MTJs, where it significantly affects the magnetization. In order to control the magnetization using spin torque effects this component needs to be known and understood. However, the magnitude of this component is difficult both to calculate [11–14] and to measure.

Sankey *et al.*, [15] measured the perpendicular spin torque component by fitting the line shape of the resonance induced by an rf current superimposed on a dc bias current on elliptical MgO MTJs. They showed that the perpendicular spin torque is quadratic in applied voltage [16], in good agreement with the first-principle calculations by Heileger and Stiles [14]. Similar measurements were also carried out by Kubota *et al.*, [17] on MgO MTJs. On the other hand, Petit *et al.* [18] measured the change in resonance frequency as a function of bias current in circular Al_2O_3 MTJs and concluded from the observed changes that the effective field due to the perpendicular torque is proportional to the biasing current density and thus changes sign with bias voltage. This is in qualitative agreement with the measurement by Li *et al.*, [19] who extracted the perpendicular torque by measuring the switching current of MgO MTJs, and by carefully accounting for heating effects due to the rather large current densities required for switching. However, since the measurements by Li *et al.* [19] were based on switching currents, the voltage range used was necessarily higher, approximately 0.5 V–1.0 V, than those of Sankey *et al.*, [15] and of Kubota *et al.* [17]. Measurements of the perpendicular spin torque effect in asymmetric MgO MTJs (i.e., the fixed layer and FL were not identical) were carried out by Oh *et al.* [20]. The perpendicular spin torque effective field was obtained by fitting plots of the FL magnetic configuration relative that of the fixed layer as function of applied external field and bias voltage, and gave the result that there is a linear term in the dependence of perpendicular spin torque effective field on bias voltage in addition to a quadratic one, in agreement with theoretical predictions [21].

Recently, one of us [22] showed, using modeling, that the effective field due to perpendicular spin torque gives rise to a linear dependence on bias voltage of the frequency of the lowest eigenmode of circularly exchange-biased trilayers of structure antiferromagnet-ferromagnet-spacer-ferromagnet. This is similar to the conclusions reached by Petit *et al.* [18]. Here, we present experimental measurements of the lowest ferromagnetic resonance frequency in MTJs of dimensions approximately 50 nm $\times$ 50 nm. The measurements show that the resonance frequency depends linearly on V_b in the range of -100 mV to $+200$ mV. We use finite-temperature micromagnetic modeling to demonstrate that this linear dependence is uniquely due to the perpendicular spin torque effective field b_J, and that it is proportional to V_b (or current density j). This is in contrast with the conclusions by Sankey *et al.*, and Wang *et al.*, [15,16], and by Kubota *et al.*, [17].

The MTJs used in the measurements were deposited using ultrahigh vacuum sputtering, and had the structure IrMn/CoFe(PL)/Ru/CoFeB(RL)/MgO/CoFeB(FL), where the FL had a thickness of about 7 nm. The pinned layer (PL) has its magnetization direction fixed by exchange-bias coupling to the antiferromagnetic IrMn. The Ru promotes a very strong antiferromagnetic coupling between the reference layer (RL) and the PL, keeping the magnetization direction of the RL fixed and antiparallel to that of the PL. Devices were patterned to a size of approximately 50 nm $\times$ 50 nm using standard lithographic techniques. High-coercivity permanent magnets were deposited on each side of the junction, and separated from it by an insulating layer about 4 nm thick. These permanent magnets supply a biasing field that keeps the equilibrium magnetization direction of the FL perpendicular to that of the RL and of the PL. We will use a coordinate system in which the RL magnetization is along $\hat{y}$, the magnetization of the FL and of the permanent magnets along $\hat{x}$, and $\hat{z}$ is perpendicular to the plane of the layers. The inset in the right panel of Fig. 1 shows a schematic cross section of the devices. In total we measured about 360 devices from two different wafers, "*A*" and "*B*." The device resistance was about 200Ω, and the devices exhibited a resistance change in an applied field of ± 1000 Oe applied perpendicularly to the field from the biasing magnets, corresponding to approximately a 20 mV signal voltage at a bias of 100 mV.

At finite temperatures, thermal agitations will excite magnetization dynamics, including ferromagnetic resonances (FMRs). The thermally-excited magnetization dynamics give rise to fluctuating resistance values. In the corresponding frequency spectrum at fixed V_b, FMR peaks are clearly observable. We observed the FMRs in our MTJs by measuring thermally induced frequency spectra at room temperature using a standard spectrum analyzer. The central result of the measurements is shown in Fig. 1. The left panel of this figure depicts the lowest FMR frequency as a function of bias voltage; each data point is an average over 200 devices from wafer *A* and 160 devices from wafer *B*. First, we note that the FMR peak frequency (f_{FMR}) is offset for devices from wafer *A* compared to devices from wafer *B*. This is explained by the fact that the configuration of the biasing magnets was slightly different in the two wafers. The FMR frequency is primarily determined by the contribution from the biasing magnets to the effective field acting on the FLs. Therefore, a change in the biasing magnets from one device design to another will lead to different f_{FMR}. Based on the measured values of f_{FMR}, we estimate the effective bias fields to be about 420 Oe and 600 Oe for wafers *A* and *B*, respectively. Second, we observe that f_{FMR} decreases in a linear fashion with increasing V_b for V_b approximately in the range of -100 mV to 200 mV, (we use the convention that V_b is positive with current flowing from RL to FL), and that the rate of decrease (the slope of f_{FMR} vs V_b) is the same for the two sets of devices, about 2 GHz/V. The right panel of Fig. 1 shows the change in f_{FMR} from its zero-bias value for the devices from wafer *A* and *B*, respectively. Here, we defined the zero-bias FMR frequency f_0 for each device as the mean of f_{FMR} at $+50$ mV and -50 mV bias voltage. Using a bivariate fit we obtain $f_{\mathrm{FMR}}(V_b) \approx f_0 + cV_b$, where c is -2.4 GHz/V and -2.1 GHz/V for wafer *A* and *B*, respectively, with standard errors less than 8×10^{-3} GHz/V. This linear change of f_{FMR} with bias voltage (or bias current density) was also observed by Petit *et al.* [18] in Al_2O_3 MTJs. There is *a priori* no reason to expect spin torque effects to be similar in MTJs with Al_2O_3 or MgO barriers, since MgO is crystalline and the transmission properties in CoFe/MgO/CoFe MTJs are determined by band matches in the minority and majority spin channels [23]. Al_2O_3 tunnel barriers, on the other hand, are amorphous and the transmission properties, and therefore

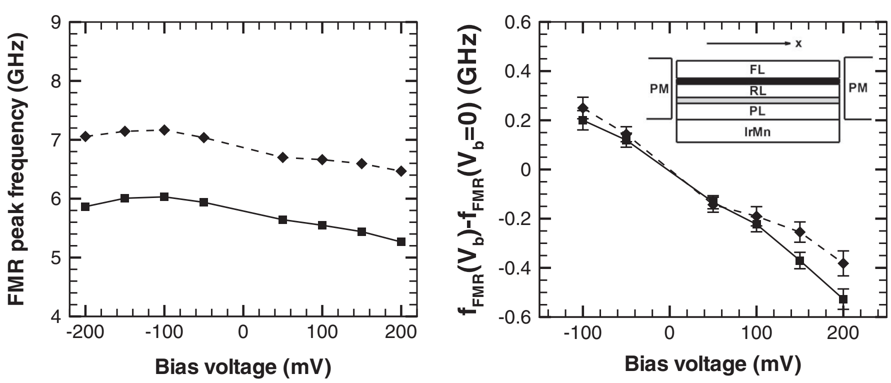

FIG. 1. Left panel: FMR peak frequency vs bias voltage for devices from wafer *A* (squares) and wafer *B* (diamonds). Right panel: Change in FMR frequency from its zero-bias value vs bias voltage.

the tunneling magnetoresistance and spin torque effects, must be determined by grosser features in the electronic structure of such MTJs.

We used micromagnetic modeling to interpret these experimental results. In the modeling, we integrated the stochastic Landau-Lifshitz-Gilbert (SLLG) [24] equation using a Heun integrator [25] at a temperature of 360 K with a time step of 5 fs. We used a mesh of size 5 nm $\times$ 5 nm in-plane and an out-of-plane spacing set by the thickness of the individual layers, which were 1.9 nm, 2.4 nm, and 7.7 nm, for PL, RL, and FL, respectively. We modeled two realizations of the MTJs with saturation magnetization densities of 1370 (1000) emu/cm^3, 983 (1200) emu/cm^3, and 630 emu/cm^3 for the PL, RL, and FL in the first (second) realization, MTJ I (MTJ II). Current-induced magnetic fields were included, as well as an exchange bias of magnitude 0.875 erg/cm^2 acting on the PL, antiferromagnetic coupling of magnitude -1.5 erg/cm^2 between the PL and the RL, and interlayer exchange between the RL and the FL of magnitude 0.05 erg/cm^2. Magnetostatic interactions were calculated using in-plane fast Fourier transforms and direct sums between the layers. The tunnel magnetoresistive ratio was set to 140% and the current spin polarization P was calculated from the Jullière formula [26] assuming similar RL and FL materials. The resistance-area product was set to 0.8 $\Omega(\mu\text{m})^2$, and the dimensionless LLG damping parameter α was set to 0.01 for all magnetic layers. In addition to the usual terms in the SLLG equations, due to the effective fields from intralayer ferromagnetic exchange, magnetostatic interactions, interlayer exchange, biasing magnets, exchange-bias (for the PL), currents, and stochastic effective fields, we added the spin torque terms

$$\boldsymbol{\tau}_{\text{RL}} = -|\gamma_e|[a_J \boldsymbol{m}_{\text{RL}} \times (\boldsymbol{m}_{\text{RL}} \times \boldsymbol{m}_{\text{FL}}) + b_J \boldsymbol{m}_{\text{RL}} \times \boldsymbol{m}_{\text{FL}}]$$

$$\boldsymbol{\tau}_{\text{FL}} = |\gamma_e|[a_J \boldsymbol{m}_{\text{FL}} \times (\boldsymbol{m}_{\text{FL}} \times \boldsymbol{m}_{\text{RL}}) + b_J \boldsymbol{m}_{\text{FL}} \times \boldsymbol{m}_{\text{RL}}].$$

Here γ_e is the electron gyromagnetic factor, a_J (b_J) the effective field due to in-plane (perpendicular) spin torque, and $\boldsymbol{m}_{\text{RL}}$ ($\boldsymbol{m}_{\text{FL}}$) is the local magnetization director in the RL (FL). We used $a_J = \frac{\hbar j P}{2eM_S t}$, where for the RL (FL) j is the current density, P is the current spin polarization, and M_S and t are the saturation magnetization and thickness of the RL (FL). The signal voltage was calculated and sampled every 0.01 ns over 100 ns for each computation of a thermally-excited noise spectrum, and the sampled signal voltage was Fourier transformed to yield a noise spectrum with a resolution of 0.01 GHz. We smoothed the numerical data by averaging over 15 consecutive points and then fit the lowest resonance peak with a Lorentzian, from which we obtained peak frequency, as well as peak width and an overall constant background noise level. With a_J fixed we calculated noise spectra for different fixed bias currents and different values of the ratio b_J/a_J for each bias current. According to the expression for a_J, this quantity is proportional to the bias current density j, or equivalently, to the bias voltage V_b, since $j = V_b/(RA)$.

First we established that the current-induced Ampère fields are not responsible for bias dependence of f_{FMR}. With a_J and b_J set to zero we calculated f_{FMR} for $V_b =$ 100 mV and $V_b = -100$ mV. The calculated spectra had the same peak frequency. Because the current-induced fields change direction when the bias voltage changes sign, there should be a difference in f_{FMR} for the two bias voltages if the current-induced fields causes f_{FMR} to depend on V_b. The fact that the peak frequencies are identical then conclusively rules out current-induced fields as being responsible for the change in f_{FMR} with V_b. Next, using $a_J = \frac{\hbar j P}{2eM_S t}$, we set $b_J = 0$ and calculated noise spectra for $V_b = 100$ mV and $V_b = -100$ mV. Again, there was no observable change in f_{FMR} with V_b, which rules out the in-plane spin torque as the source of change in f_{FMR} with V_b, since a_J is odd in V_b. We next therefore performed a series of simulations for two different MTJ models at fixed $V_b = \pm 100$ mV and ± 50 mV and different values of b_J/a_J for each value of V_b in order to examine the effect of b_J on f_{FMR}.

Figure 2 depicts the modeled f_{FMR} as a function of b_J/a_J for MTJ I and MTJ II for fixed $|V_b| = 100$ mV. (Because the FL and the biasing magnet configurations were not changed, f_{FMR} is approximately equal for the two MTJs). The key point, as depicted in the figure, is that the f_{FMR} is a linear function of b_J/a_J for fixed V_b, and decreases (increases) for V_b positive (negative), in agreement with the experimental measurements (Fig. 1). The magnitude of the observed dependence of f_{FMR} on V_b is also in agreement with the modeling results. Figure 3 shows f_{FMR} plotted against V_b for fixed values of b_J/a_J. This figure shows that the calculated change in f_{FMR} as a function of v_b agrees well with the measured values for $b_J/a_J \approx 1$. From this, we conclude that in order to obtain

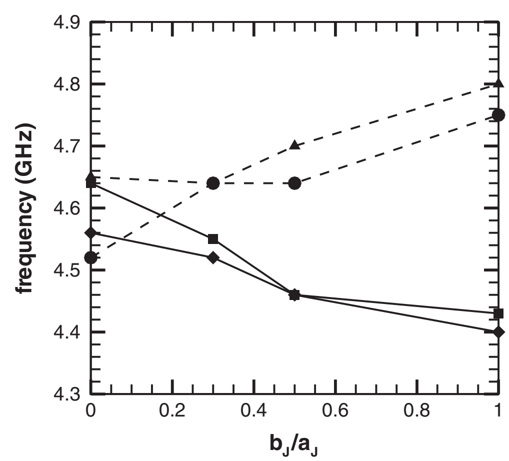

FIG. 2. Calculated f_{FMR} as plotted against b_J/a_J for MTJ I positive (square) and negative bias (triangle), and for MTJ II positive bias (diamond) and negative bias (circle).

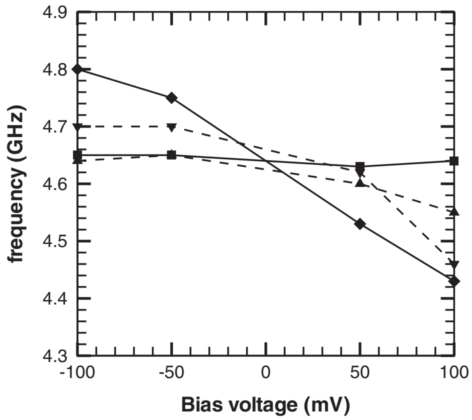

FIG. 3. Calculated f_{FMR} for MTJ I as function of V_b for $b_J/a_J = 0$ (solid line, squares), $b_J/a_J = 0.3$ (dashed line, triangles), $b_J/a_J = 0.5$ (dashed line, inverted triangles), and $b_J/a_J = 1.0$ (solid line, diamonds).

agreement with the experimental data, b_J must be a linear function of j or V_b. This is in agreement with the observations by Petit *et al.* [18] and by Li *et al.* [19] (note that our bias voltages were much lower than those used by Li *et al.*), but in contrast to the conclusions by Sankey *et al.*, and Wang *et al.*, [15,16], and by Kubota *et al.*, [17]. From our obtained linear relation between b_J and j (or V_b), we can estimate an effective field $b_J \approx 11 \times 10^{-6}$ Oe(cm)^2/A. This is one order of magnitude larger than the value of 1×10^{-6} Oe(cm)^2/A estimated by Petit *et al.* [18], which is not unreasonable since the tunneling magnetoresistive ratio used here (140%) is almost one order of magnitude larger than that used by Petit *et al.* [18]. Although our junctions are slightly asymmetric, we do not find any significant quadratic term of b_J in bias voltage, in contrast with the results by Oh *et al.* [20].

In summary, we have measured the FMR peak frequency of two sets of MTJs biased by permanent magnets. The measurements show that the FMR peak frequency decreases linearly with increasing bias voltage for voltages in the range of -100 mV to $+200$ mV. Detailed micromagnetic modeling makes clear that the change in FMR peak frequency is due to the perpendicular spin torque, and that the FMR frequency change, for fixed bias voltage, is proportional to the perpendicular spin torque effective field. We conclude that the perpendicular spin torque is proportional to current density or bias voltage, in contrast with other works on MgO tunnel junctions [15–17], but in agreement with the conclusions by Li *et al.*, [19] on MgO MTJs, and by Petit *et al.* [18] on Al_2O_3 MTJs. We find that the magnitude is approximately equal to the in-plane spin torque effective field. Our work also suggests a very direct way of measuring the perpendicular spin torque effective field. This may help to enable accurate determination and control of this spin torque component, which is necessary for the use of spin torque to manipulate MTJ spintronics devices [27].

*Present and permanent address: Materials Science Division, Argonne National Laboratory, Argonne, IL 60439.
heinonen@anl.gov

[1] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[2] L. Berger, Phys. Rev. B **54**, 9353 (1996).
[3] J. A. Katine, F. J. Albert, R. A. Buhrman, E. B. Myers, and D. C. Ralph, Phys. Rev. Lett. **84**, 3149 (2000).
[4] M. Tsoi, Nature (London) **406**, 46 (2000).
[5] S. I. Kiselev, Nature (London) **425**, 380 (2003).
[6] W. Rippard, M. Pufall, S. Kaka, S. Russek, and T. Silva, Phys. Rev. Lett. **92**, 027201 (2004).
[7] S. Zhang, P. M. Levy, and A. Fert, Phys. Rev. Lett. **88**, 236601 (2002).
[8] K. Xia, P. J. Kelly, G. E. W. Bauer, A. Brataas, and I. Turek, Phys. Rev. B **65**, 220401(R) (2002).
[9] M. A. Zimmler, B. Özyilmaz, W. Chen, A. D. Kent, J. Z. Sun, M. J. Rooks, and R. H. Koch, Phys. Rev. B **70**, 184438 (2004).
[10] S. Urazhdin, N. O. Birge, W. P. Pratt, and J. Bass, Phys. Rev. Lett. **91**, 146803 (2003).
[11] I. Theodonis, N. Kioussis, A. Kalitsov, M. Chshiev, and W. H. Butler, Phys. Rev. Lett. **97**, 237205 (2006).
[12] Z. Li and S. Zhang, Phys. Rev. B **69**, 134416 (2004).
[13] D. M. Apalkov and P. B. Visscher, Phys. Rev. B **72**, 180405(R) (2005).
[14] C. Heiliger and M. D. Stiles, Phys. Rev. Lett. **100**, 186805 (2008).
[15] J. C. Sankey, Y.-T. Cui, J. Z. Sun, J. C. Slonczewski, R. A. Buhrman, and D. C. Ralp, Nature Phys. **4**, 67 (2008).
[16] C. Wang, Y.-T. Cui, J. Z. Sun, J. A. Katine, R. A. Buhrman, and D. C. Ralph, Phys. Rev. B **79**, 224416 (2009).
[17] H. Kubota, A. Fukushima, K. Yakushiji, T. Nagahama, S. Yuasa, K. Ando, H. Maehara, Y. Nagamine, K. Tsunekawa, and D. D. Djayaprawira *et al.*, Nature Phys. **4**, 37 (2008).
[18] S. Petit, C. Baraduc, C. Thirion, U. Ebels, Y. Liu, M. Li, P. Wang, and B. Dieny, Phys. Rev. Lett. **98**, 077203 (2007).
[19] Z. Li, S. Zhang, Z. Diao, Y. Ding, X. Tang, D. M. Apalkov, Z. Yang, K. Kawabata, and Y. Huai, Phys. Rev. Lett. **100**, 246602 (2008).
[20] S.-C. Oh, S.-Y. Park, A. Manchon, M. Chshiev, J.-H. Han, H.-W. Lee, J.-E. Lee, K.-T. Nam, Y. Jo, and Y.-C. Kong *et al.*, Nature Phys. **5**, 898 (2009).
[21] J. Xia, G. E. W. Bauer, and Brataas, Phys. Rev. B **77**, 224419 (2008).
[22] O. G. Heinonen, Phys. Rev. B **81**, 054405 (2010).
[23] Z. Zhang and W. Butler, Phys. Rev. B **70**, 172407 (2004).
[24] W. Brown, Phys. Rev. **130**, 1677 (1963).
[25] J. Garcia-Palacios and F. Lazaro, Phys. Rev. B **58**, 14 937 (1998).
[26] M. Jullière, Phys. Lett. A **54**, 225 (1975).
[27] See, for example, Y. Zhao and J. Akerman, Appl. Phys. Lett. **94**, 112503 (2009).