Bias dependences of in-plane and out-of-plane spin-transfer torques in symmetric MgO-based magnetic tunnel junctions

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(Received 9 November 2009; revised manuscript received 4 February 2010; published 15 April 2010)

We investigate the bias dependences of in-plane and out-of-plane spin-transfer torque by employing magnetic noise measurement in symmetric MgO-based magnetic tunneling junction devices. The measured power spectra densities of magnetic noise are successfully analyzed by the fluctuation-dissipation theorem with an imaginary part of transverse susceptibility including spin-transfer torque contributions. We find that the in-plane component has a linear dependence of the bias voltage, while the out-of-plane component has a quadratic dependence. These results are well consistent with the noise amplitude analysis, neglecting the Joule heating effect with small bias voltage.

DOI: 10.1103/PhysRevB.81.134419   PACS number(s): 75.75.−c, 76.50.+g, 85.75.Dd, 05.40.−a

I. INTRODUCTION

Since the discovery of the spin-transfer torque (STT),[1] it has been received lots of attentions due to not only its potential application such as magnetic random access memory[2] but also its exotic physics.[3–5] It has been proposed theoretically[6] and confirmed experimentally[7,8] that the role of the out-of-plane component of STT is negligible in fully metallic nanopillars, while it is important in magnetic tunnel junction (MTJ) devices because of the different contributions of Brillouin zone integral.[9]

In theoretical point of view, the bias dependences of the in-plane and out-of-plane components of STT give essential information for further understanding of the STT physics.[10–13] However, the bias dependence of out-of-plane STT component is not clear yet because of controversies among available experimental data:[7,8,11,14–16] While Kubota *et al.*[7] and Sankey *et al.*[8] reported that the out-of-plane STT has a quadratic bias dependence, Petit *et al.* claimed a linear dependence[14] or a mixture of linear and quadratic dependences.[15] Li *et al.*[11] argued that the out-of-plane STT depends on the power, that is, the product of current and bias voltage, and its sign changes with the polarity of the current due to the energy dependence of inelastic scattering in high bias voltage region. Deac *et al.*[17] also reported linear and quadratic dependence of the in-plane and out-of-plane STTs on the bias voltage, respectively. The controversies may be caused by additional effects to that of STTs, such as the nonlinear spin dynamics, inelastic scattering, and Joule heating.

II. EXPERIMENTAL

In this study, we investigate the bias dependence of the STT in MgO-based MTJs in low bias region, in order to exclude those additional effects. We measure the thermally excited ferromagnetic resonance (TE-FMR) with the current injection and analyze the experimental data using different effects of in-plane and out-of-plane STTs on the TE-FMR. The symmetric MTJs of SiO_2 substrate/buffer layer / PtMn (15) / CoFe (2.6) / Ru (0.85) / $Co_{60}Fe_{20}B_{20}$ (3.0) / MgO(0.85) / $Co_{60}Fe_{20}B_{20}$(3.0)/capping layer (thickness in nanometers) were patterned into nanopillars with 100×200 nm^2. The resistance-area product for parallel (P) and antiparallel (AP) states are 4.38 and 7.36 $\Omega\ \mu$m^2, respectively. Our experimental setup and sample structure are schematically shown in Fig. 1 with corresponding coordinate system. The magnetic noise spectra at room temperature were taken with a spectrum analyzer (Agilent E4448A) in the GHz frequency range, where a 55 dB preamplifier was used. The data were subtracted from the background noise induced by the measurement setup and normalized by the transmission function. By definition in our experiments, the positive current represents that the electrons flow from the free to the reference layer, favoring the antiparallel magnetic alignment,

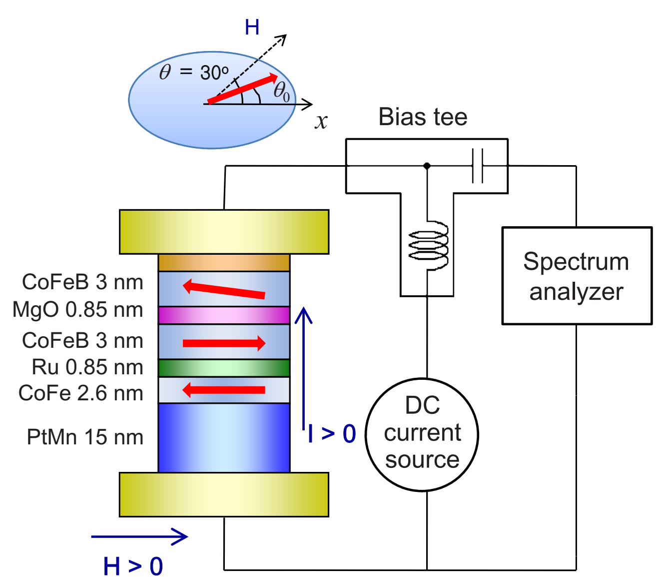

FIG. 1. (Color online) Schematics of the sample structure, magnetic noise spectra measurement setup, and the corresponding coordinate system.

and the positive (negative) magnetic field favors the parallel (antiparallel) alignment.

III. RESULTS AND DISCUSSION

The magnetic noise spectra were measured with a constant current mode,[18] and the applied current (I) was converted into the bias voltage (V) in the analysis of data. We paid our attention only to the TE-FMR case where the in-plane STT enhances the damping torque and stabilizes the P and AP states in the negative and positive bias voltages, respectively. Like Ref. 15, we find additional edge mode peaks in the noise spectra; however, we focus only the lower-frequency spectra in our analysis. The external magnetic fields of +60 Oe (for P state) and −60 Oe (for AP state) are applied to an angle 30° from the magnetization direction (x axis) of the reference layer in order to tilt the magnetization orientation of the free layer. The selected magnetic noise spectra were shown in Figs. 2(a) and 2(b) with nonlinear regression results for $I=\pm 0.1$, ± 0.5, and ± 1.0 mA for P and AP states, respectively. More details of Figs. 2 will be discussed later.

The magnetic noise spectrum $V_n(\omega)$ is related with the imaginary part of the transverse susceptibility, $\chi^i_{yy}(\omega)$, by the fluctuation-dissipation theorem:[15,19]

$$V_n(\omega) = I\Delta R \sin\theta_0 \sqrt{\frac{k_B T}{\omega\mu_0 M_s^2 V_0}\chi^i_{yy}(\omega)}, \tag{1}$$

where I, ΔR, θ_0, k_B, T, μ_0, M_s, and V_0 are the current, magnetoresistance, actual tilting angle between the magnetization directions of free layer from the x axis, Boltzmann constant, temperature, permeability of vacuum, saturation magnetization, and the volume of sample, respectively. The imaginary part of the transverse susceptibility can be derived from the modified Landau-Lifshitz-Gilbert equation including STT effect:[15]

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M}\times(\vec{H}-b_J\vec{p}) + \frac{\alpha}{M_s}\vec{M}\times\frac{d\vec{M}}{dt} + \gamma\frac{a_J}{M_s}\vec{M}\times(\vec{M}\times\vec{p}). \tag{2}$$

The $\vec{p}$ is a unit vector of the magnetization direction of the reference layer. Then, the imaginary part of the transverse susceptibility is given by

$$\chi^i_{yy}(\omega) = \gamma M_s\omega\frac{\gamma H^p_x\Lambda - \alpha\Omega^2}{\Omega^4+\omega^2\Lambda^2}. \tag{3}$$

We followed the notation of Ref. 15 and let the direction of external magnetic field H_{ext} at an angle θ from the reference layer magnetization (x axis). In our measurement condition, (H_{ext}=+/−60 Oe, and $\theta=\pm 30°$), the actual magnetization tilting angle θ_0 is small ($\theta_0 \ll 1$). According to the micromagnetic simulation, we find that the average θ_0 value is less than 10°, that is $\cos(\theta_0)\sim 0.984\sim 1$. Therefore, the x component of magnetization approaches the saturation magnetization ($M_x \sim M_s$), then we define follows:

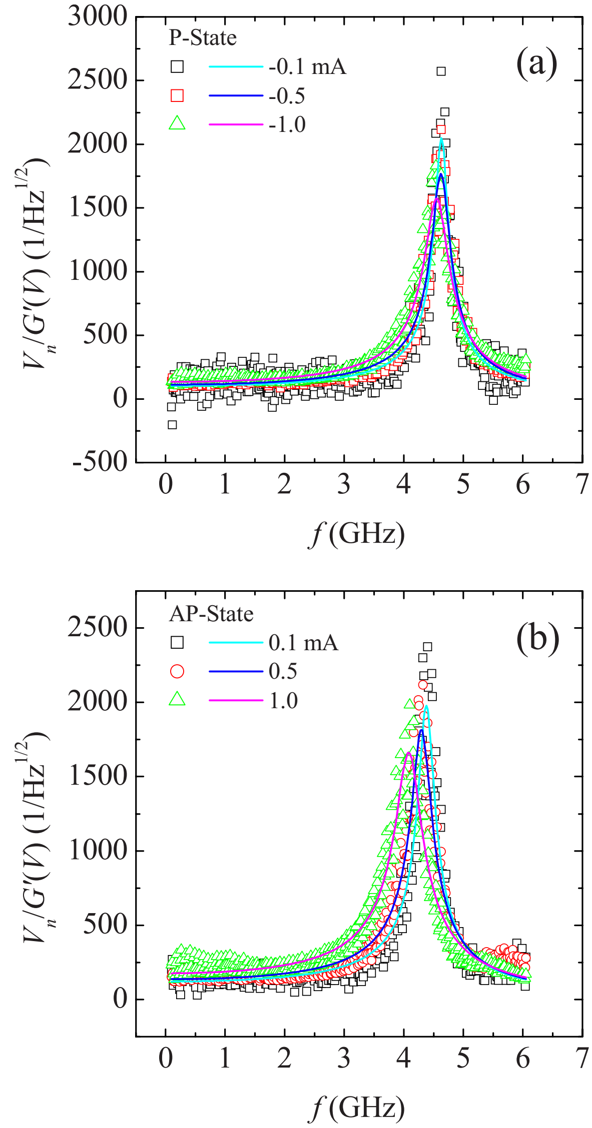

FIG. 2. (Color online) Selected magnetic noise spectra data (for $I=\pm 0.1, \pm 0.5, \pm 1.0$ mA) with nonlinear regression results for (a) P state and (b) AP state.

$$H^0_y = \cos\theta H_{ext} + (N_y - N_x)M_s,$$
$$H^0_z = \cos\theta H_{ext} + (N_z - N_x)M_s, \tag{4}$$

$$H^p_y = H^0_y - \varepsilon b_J, \quad H^p_z = H^0_z - \varepsilon b_J, \tag{5}$$

$$\Lambda = \gamma[\alpha(H^p_y + H^p_z) - 2\varepsilon a_J], \tag{6}$$

$$\Omega^2 = \omega_0^2 - (1+\alpha^2)\omega^2, \tag{7}$$

$$\omega_0^2 = \gamma^2[H^p_y H^p_z + a_J^2]. \tag{8}$$

Here, $N_{x,y,z}$ are the demagnetization factors of each direction ($N_x < N_y \ll N_z$ for thin film ellipse), and α is the Gilbert damping parameter. $\varepsilon = \pm 1$ for P and AP states, and the a_J and b_J terms are the magnitude of the in-plane and out-of-plane STT components in the unit of field, respectively. By the definitions, the Λ and ω_0 are related with linewidth and resonance frequency of $\chi^i_{yy}(\omega)$ spectrum, respectively. For the bias dependence of Λ and ω_0, see supplemental material.[26] According to Eq. (6), the Slonczewski a_J term alters the linewidth by increasing or decreasing the damping torque, while the fieldlike b_J term behaves as an additional field term. Since the resonance frequency depends on the effective field, the b_J term manifests itself as a resonance frequency shift. Therefore, the variations of linewidth and resonance frequency are signatures of the in-plane and out-of-plane STT contributions in magnetic noise spectra, respectively.[11,14,15]

The saturation magnetization was determined to be $M_s = 1.3\times10^3$ emu/cm^3 from the external magnetic field dependence of resonance frequency considering the Kittel formula (not shown). From the measured magnetic noise spectra $V_n(\omega)$ for the smallest V (corresponding $I=\pm0.1$ mA), where the STT effect is negligible, we obtained damping parameter α ($\alpha^{P}=0.0055$, $\alpha^{AP}=0.0067$) and effective field ($H^{P}_{Eff}=100$ Oe, $H^{AP}_{Eff}=80$ Oe) by the nonlinear regression processes with zero STT effect. Here $H^{P,AP}_{Eff}$ are effective field are included the external applied field, anisotropy field, and coupling field from the reference layer. Therefore, the origin of difference between H^{P}_{Eff} and H^{AP}_{Eff} is a coupling field between the free and reference layers, for example, interlayer exchange coupling, orange-peel coupling, and magnetostatic dipolar interaction. In our case, the most probable origin is the dipole interaction between the free and reference layers. With the predetermined values of H_{Eff} and α, here by taking single value of $\alpha=0.006$ for P and AP states, we performed nonlinear regression process with a_J and b_J as fitting parameters for the magnetic noise spectra at finite bias voltages. Here, it should be pointed out that two more fitting parameters,[19] scaling factor G and offset, were used. The scaling factor G and offset are related with impedance mismatch and background noise. Then, Eq. (1) can be rewritten by the following expression, here we skipped the offset:

$$V_n(\omega) = GI\Delta R \sin\theta_0 \sqrt{\frac{k_BT}{\omega\mu_0 M_s^2 V_0}\chi^i_{yy}(\omega)} = G'(V)\sqrt{\frac{k_BT}{\omega\mu_0 M_s^2 V_0}\chi^i_{yy}(\omega)}. \quad (9)$$

Even though the bias voltage dependence of ΔR is predetermined by separate dc measurements, we redefine the bias dependence of scaling factor $G'(V)$ because the magnetization tilting angle θ_0 is also a function of the bias voltage. With four fitting parameters and proper H_{Eff} and α values, we obtain an excellent agreement with the measured magnetic noise spectra in Figs. 2(a) and 2(b). In these plots, the raw experimental data are scaled with the factor $G'(V)$, and the suppression of noise peak with the increment of current are clearly observed. The resulting values of a_J and b_J are plotted as a function of bias voltage in Figs. 3 and 4.

In Fig. 3, it is clearly shown that the in-plane STT component of a_J is a linear function of bias voltage. By defining $a_J=a_0+a_1V$, we have $a_1^{P}=122.1(\pm2.7)$ Oe/V [$=9720\pm214$ A/(V·m)] and $a_1^{AP}=-66.4(\pm4.0)$ Oe/V [$=-5285\pm318$ A/(V·m)]. These values are similar to those

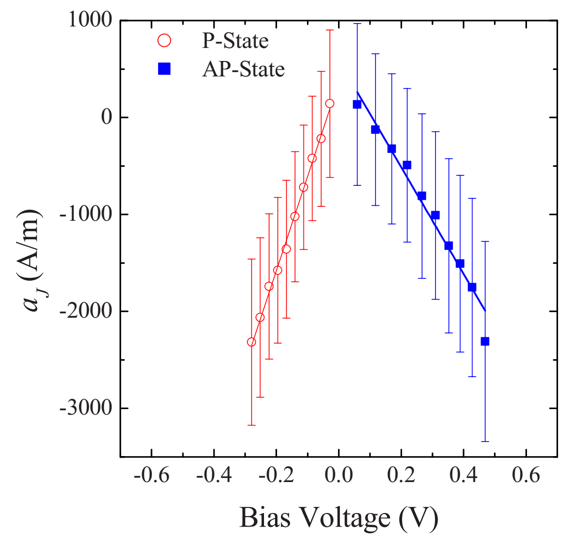

FIG. 3. (Color online) In-plane STT a_J term as a function of bias voltage V for P state (open circles) and AP state (solid squares). The hollow rectangles represent nonlinear regression results for a_J from the magnetic noise spectra and solid lines are linear fit of $a_J=a_0+a_1V$.

reported by Petit *et al.*[15] (=140 Oe/V) and Deac *et al.*[17] (=24∼660 Oe/V that depends on the bias voltage). We can also express our experimental data with the concept of torkance given by $d\tau/dV$,[20] which are $\frac{d\tau_\parallel}{dV}|_{P}=2.28$ and $\frac{d\tau_\parallel}{dV}|_{AP}=1.24$ ($\hbar/2e$ kΩ^{-1}). These values are larger than those reported by other group[16] and simple theoretical expectation.[21] Furthermore, it should be pointed out that the values of a_1^{P} and a_1^{AP} are different by a factor of 2. According to the theoretical predictions for symmetric MTJs, they must be same. The origin of these discrepancies is not clear yet, and further investigations will be required. Here, it should be mentioned that we have adjusted H_{Eff} and α in order to minimize a_0 because it must be zero by its physical definition.

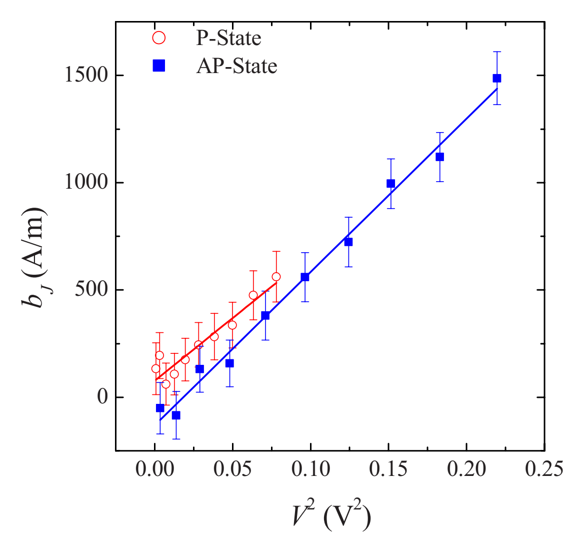

FIG. 4. (Color online) Out-of-plane STT b_J term as a function of V^2 for P state (open circles) and AP state (solid squares). The hollow rectangles represent nonlinear regression results for b_J from the magnetic noise spectra and solid lines are linear fit of $b_J=b_2V^2$.

Theoretically, the bias voltage dependence of b_J has been predicted as a quadratic function for symmetric MTJs.[6,10] In our experiment, the temperature increment by the Joule heating may affect b_J, because it can cause the shift of resonance frequency as b_J does. When the temperature increases, M_s of ferromagnetic material generally decreases. It leads to a reduction of the effective field so that the resonance frequency shifts to a lower frequency. The frequency shift is a linear function of the temperature for small variation of temperature or M_s,[19] and the temperature increment of MTJ is proportional to the square of current.[22] Thus, the frequency shift due to the Joule heating is a quadratic function of the bias voltage. On the other hand, another possible origin is the Oersted field created by a running current. However, this effect is a linear function of the bias voltage, so that it can be distinguishable. Therefore, it is not easy to distinguish the contribution of the fieldlike b_J from the Joule heating in the resonance frequency shift measurement.

First, let us ignore the effect of the Joule heating in our analysis. Figure 4 shows that b_J is a quadratic function of bias voltage V for P and AP states. b_J is well described by the relation of $b_J = b_0 + b_2 V^2$, where $b_2^{\mathrm{P}} = 89.8(\pm 2.9)$ Oe/V^2 [7148 ± 230 A/(V$^2 \cdot$m)] and $b_2^{\mathrm{AP}} = 73.5(\pm 8.5)$ Oe/V^2 [5850 ± 677 A/(V$^2 \cdot$m)]. Here, b_0 is the out-of-plane STT at zero bias, so-called interlayer exchange coupling term. These values are comparable with those reported in Ref. 15 (=220 Oe/V^2), Ref. 17 (=180 Oe/V^2), and Ref. 11 (=30–50 Oe/V^2). We also convert the out-of-plane STT to torkance for comparison with Ref. 16, $\frac{d\tau_\perp}{dV}|_{\mathrm{P}} = 0.46$ and $\frac{d\tau_\perp}{dV}|_{\mathrm{AP}} = 0.64$ ($\hbar/2e$ kΩ^{-1}). It should be emphasized that the b_J always reduces the resonance frequency, i.e., it decreases the effective field term whether P or AP state.

Second, let us consider the Joule heating effect in our resonance frequency shift analysis. Sankey *et al.*[8] carefully analyzed the effect of Joule heating and concluded that it does not affect their results. In some studies,[11,14,15,23,24] they argued that the heating is the main reason of the frequency shift. As aforementioned, because the temperature increment causes the redshift of resonance frequency as a result of the reduction of M_s, it is impossible to separate the b_J and temperature contributions from the resonance frequency analysis without any exact information of the sample temperature. Therefore, we would introduce another analysis method. Petit *et al.*[15] argued that the noise peak amplitude has important physical meaning, but they did not quantitatively analyze the noise peak amplitude. Here, we perform successful quantitative analysis in the noise peak amplitude. Let us recall Eq. (9), and rewrite it at its peak value,

$$V_n(\omega_M) = G'(V)\sqrt{\frac{k_B T}{\omega_M \mu_0 M_s^2 V_0}\chi_{yy}^i(\omega_M)}, \qquad (10)$$

where ω_M is the angular frequency at the resonance peak. Then the above equation can be rewritten as

$$\left(\frac{V_n(\omega_M)}{G'(V)}\right)^2 = \frac{k_B T}{\omega_M \mu_0 M_s^2 V_0}\chi_{yy}^i(\omega_M). \qquad (11)$$

With Eq. (3), $\chi_{yy}^i(\omega_M)$ can be approximated around its peak and it reads

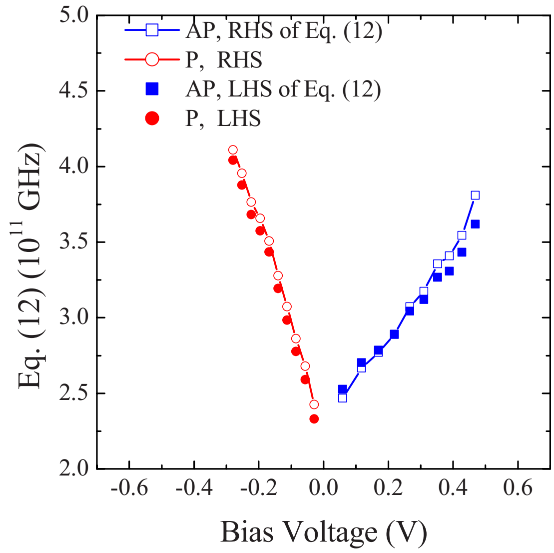

FIG. 5. (Color online) RHS (open symbols with lines) and LHS (solid symbols) of Eq. (12) are depicted together for P state (circles) and AP state (squares). The LHS is obtained from the peak amplitudes, while the RHS is calculated from predetermined a_J and b_J.

$$\left(\frac{V_n(\omega_M)}{G'(V)}\right)^{-2} \sim \frac{\mu_0 M_s V}{\gamma k_B T}\left(\frac{\omega_M^2}{\gamma H_x^p}\right)(\gamma[\alpha(H_x^p + H_y^p) - 2a_J]). \qquad (12)$$

Here, it should be pointed out that the left-hand side (LHS) of Eq. (12) is explicitly temperature independent, while the right-hand side (RHS) of Eq. (12) is explicitly temperature dependent. According to this equation, we could obtain the LHS of Eq. (12) from the measured noise peak amplitude and scaling factor $G'(V)$, and calculate the RHS of Eq. (12) from the a_J and b_J values predetermined by linewidth and resonance frequency with a constant temperature assumption. This implies that the LHS and RHS results stem from independent measurements. Furthermore, the temperature dependence is appeared explicitly as $k_B T$ term and implicitly through M_s in RHS. The results are plotted together in Fig. 5, showing excellent agreements each other. If the temperature variation between the set temperature and the sample temperature is large, the disagreement between LHS and RHS should be noticeable. Very small deviation only in the AP state is observed at high bias voltages (>0.3 V). According to Eq. (12), the RHS is an approximately linear function of bias voltage with the slope of $(\mu_0 M_s V/\gamma k_B T)(\omega_M^2/\gamma H_x^p)(-2a_1)$ for a constant temperature. Therefore, if the temperature increases, then the slope will decrease. In order to obtain better agreement, we have to insert a larger temperature to the RHS for $V > 0.3$ V in the AP state. It reflects the possible increment of the temperature in this high bias voltage region. Except this high voltage region, the overall disagreement is negligible, implying that the temperature increment is not serious when determining b_J in our analysis. Such small Joule heating also agrees with independent numerical simulations with finite element method.[25] Therefore, the obtained b_J is meaningful even though it includes small Joule heating effect.

IV. CONCLUSION

In conclusion, explicit dependence of bias voltage with in-plane and out-of-plane spin-transfer torque has been established by magnetic noise measurement in symmetric MgO-based magnetic tunneling junction devices. By analyzing the measured power spectra densities of magnetic noise with the fluctuation-dissipation theorem, we demonstrate that the in-plane STT component exhibits a linear form of the bias voltage, while the out-of-plane component exhibits a quadratic form. These results are well consistent with the noise amplitude analysis, reflecting the negligible Joule heating at low bias voltages.

ACKNOWLEDGMENTS

This work was supported by the IT R&D program of MKE/KEIT (Grant No. 2009–F-004–01), by the Korea Research Foundation (KRF) grant funded by the Korea government (MEST) (Grant No. KRF-2009-0074625), and by Nano R&D (Grant No. 2008-02553) programs through the Korea Science and Engineering Foundation funded by the Ministry of Science & Technology.

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