Current fluctuations and magnetization dynamics symmetry in spin-torque-induced magnetization switching

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(Received 19 May 2008; revised manuscript received 26 June 2008; published 18 July 2008)

We studied spin-torque-induced magnetization switching with current fluctuations using models and experiment measurements. It was found that the efficiency of accelerating magnetization reversal by noisy current strongly depends on the symmetry of magnetization dynamics. The efficiency of noisy current on accelerating magnetization switching is quite different for a magnetic thin-film element without rotational symmetry and a uniaxial anisotropy magnetic element with rotational symmetry. The study reveals that interactions between magnetization dynamics symmetry and system fluctuations are critical for predicting the switching behavior of spin-torque excited magnetic system with noise.

DOI: 10.1103/PhysRevB.78.024417 PACS number(s): 85.75.−d

I. INTRODUCTION

Magnetization switching under spin-torque current[1,2] has received increasing attention as a novel magnetization switching mechanism.[3] Polarized current induced spin-torque provides a path to switch ferromagnetic order parameter without using external magnetic field. One example is a promising new mechanism for the write operation of nanomagnetic memory element.[4] The obstacles that prevent wide application of spin-torque current induced magnetization switching are high critical switching current and switching current variations. For a magnetic thin-film element in nanomagnet structures, the critical spin-torque switching current magnitude is dominated by the out-of-plane demagnetization factor.[5] This is quite different from the case of magnetic switching driven by magnetic field (where the critical switching magnetic-field magnitude is determined by the difference between lateral demagnetization factors). The fundamental physics behind this is the broken rotational symmetry of the spin-torque excited thin-film magnetization dynamics. Understanding this is very important for the study and design of magnetic structures with efficient spin-torque switching.

For magnetic nanostructures, fluctuations are inevitable. It is well known that random thermal fluctuations at finite temperature lower critical switching current, and the critical switching current magnitude strongly depends on the temperature and the measurement time scale. Recently, supplementing dc with a noisy current component has been proposed to reduce critical switching current.[6] The idea is that the current fluctuations were combined to thermal fluctuations to help spin-torque-induced magnetization switching. Theoretical analysis in Ref. 6 shows that for a magnetic element with coercivity of 50 mT (500 Oe) and magnetic moment of 10^{-17} Am^2 (10^{-14} emu), the current induced magnetization switching time can be reduced drastically (orders of magnitude) by a modest level of externally generated current noise in the order of 10^{-20} C^2/s. While the prediction in Ref. 6 is based on a uniaxial anisotropy magnetic element with rotational symmetry magnetization dynamics, this rotational symmetry is usually broken for thin-film element in real spin valve or magnetic tunneling junction (MTJ) device. As discussed above, magnetization dynamics symmetry plays important roles in spin-torque-induced magnetization switching, even for deterministic magnetic systems without fluctuations. Thus, it is important to explore magnetization dynamics symmetry in spin-torque excited magnetic system with fluctuations. In this paper, we measure and model noisy current effects on spin-torque magnetization switching for a MTJ thin film. Our study shows that the efficiency of accelerating magnetization reversal by noisy current strongly depends on the symmetry of magnetization dynamics. The efficiency of noisy current on accelerating magnetization switching is quite different for a magnetic thin film without rotational symmetry and a uniaxial anisotropy magnetic element with rotational symmetry. Our study reveals that understanding the interaction between magnetization dynamics symmetry and system fluctuations is important for exploring magnetic structures with efficient spin-torque-induced magnetization switching.

II. EXPERIMENT MEASUREMENT

To study MTJ switching under noisy current in a wide time range, a special probing assembly was used, which covered from dc up to gigahertz range. It included a Tektronix-Sony 710 arbitrary waveform generator (AWG710), a picoprobe microwave probe, a Keithley 2400 source meter, and a noise generator 7110 (ASIG). The AWG710 allowed pulse duration to vary from larger than 1 s to as short as 250 ps. The bandwidth of picoprobe was from dc to 40 GHz. The bandwidth of noise generator can reach 1.5 GHz. After each pulse was applied, the device resistance was measured by using Keithley 2400 source meter. The measurement procedure for determining the critical switching current for a particular current duration were as follows: (1) a dc was applied through the device, the current was sufficient to consistently set the device into the antiparallel (or parallel) state; (2) an opposite polarity current pulse with both signal and noisy components at a certain pulse duration was applied through the device, and the device resistance was measured; and (3) The applied pulse amplitude was increased until the device state was changed. This procedure was repeated 100 times to get switching current statistical ensembles.

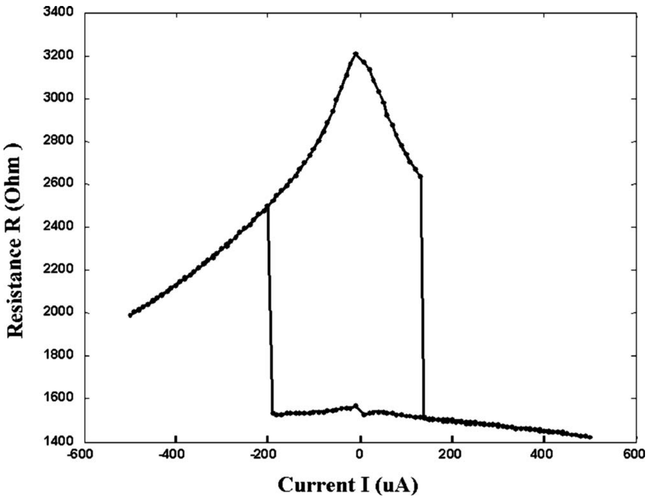

FIG. 1. Measured resistance versus current for magnetic tunneling junction used in the experiment.

Figure 1 shows the resistance versus current for the MTJ device in the measurement. Figure 2 shows examples of measured critical switching current versus dc pulse duration for a wide range of noisy current magnitude. The measurement shows no obvious effects of noisy current on magnetization switching. The thin film in the experiment has a dimension of 160 nm in length, 80 nm in width, and 2 nm in thickness. The coercivity of the thin film is around 250 Oe and the magnetic moment is about 2.56×10^{-14} emu. The maximum noisy current spectral in the experiment can reach 10^{-19} C^2/s. Although we are using a magnetic tunneling junction instead of a spin valve, the magnetic parameters and noisy current magnitudes in the experiment are comparable to parameters in Ref. 6. While Ref. 6 predicts a drastic acceleration of magnetization switching by noisy current, our experiment shows no obvious effect of noisy current on magnetization switching for a wide range of noise magnitudes and measurement time scale. Analysis in Sec. III will show that noisy current effect on accelerating magnetization switching is quite different for a magnetic thin-film element without rotational symmetry and a uniaxial anisotropy magnetic element with rotational symmetry.

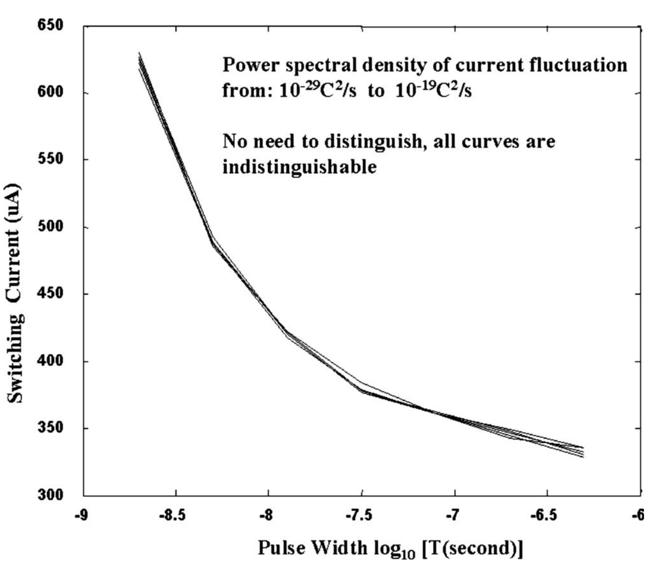

FIG. 2. Measured MTJ critical switching current versus dc pulse duration for a wide range of noisy current power spectral density. The multiple curves represent data taken at different noise values, and there is no need to distinguish among them as they are all effectively indistinguishable.

III. THEORETICAL ANALYSIS

The magnetization dynamics in the free layer of MTJ is described by the stochastic Landau-Lifshitz-Gilbert equation with the spin-torque term at finite temperature,

$$\frac{d\vec{m}}{dt} = -\alpha\vec{m}\times[\vec{m}\times(\vec{h}_{\mathrm{eff}}+\vec{h}_{\mathrm{fluc}})] - \vec{m}\times[(\vec{h}_{\mathrm{eff}}+\vec{h}_{\mathrm{fluc}})+\beta\vec{m}\times\vec{p}], \quad (1)$$

where $\vec{m}$ is the normalized magnetization and t is the normalized time. $\vec{h}_{\mathrm{eff}}=\vec{H}_{\mathrm{eff}}/M_s=\frac{\partial\varepsilon}{\partial\vec{m}}$ is the normalized effective magnetic field corresponding to a normalized energy density ε and $\vec{h}_{\mathrm{fluc}}$ is the thermal fluctuation field at finite temperature. α is the damping parameter, $\vec{p}$ is a unit vector pointing to the spin-polarization direction, and $\beta=\eta hI/2eM_s^2V$ is the normalized spin-torque polarization magnitude, where η is the polarization efficiency, V is the element volume, and I is the applied current. The magnitude of thermal fluctuation term in Eq. (1) is determined by fluctuation-dissipation condition at room temperature as in Ref. 7. For a current with both dc and noisy components, $I=I_0+I'$ and $\beta=\beta_0+\beta'$, where the prime represents Gaussian white fluctuations.

Equation (1) can be written in the spherical coordinate as a set of stochastic differential equations,

$$d\theta=\left(-\frac{1}{\sin\theta}\frac{\partial\varepsilon}{\partial\varphi}-\alpha\frac{\partial\varepsilon}{\partial\theta}+\frac{\delta}{\tan\theta}+\beta_0\sin\theta\right)dt + \sqrt{2\delta_I}\sin\theta\xi_3\sqrt{dt}+\sqrt{2\delta_T}\xi_1\sqrt{dt},$$

$$\sin\theta d\varphi=\left(\frac{\partial\varepsilon}{\partial\theta}-\frac{\alpha}{\sin\theta}\frac{\partial\varepsilon}{\partial\varphi}\right)dt+\sqrt{2\delta_T}\xi_2\sqrt{dt}, \quad (2)$$

where ξ_1,ξ_2,ξ_3 are Gaussian random variables with zero mean and variance one. $\delta_T=\frac{\alpha\gamma k_BT}{M_s^2V}$ is the thermal fluctuation magnitude and $\delta_I=\frac{1}{4M_s}(\frac{\eta\gamma h}{eM_sV})^2\mathrm{PSD}$ is the current fluctuation magnitude with PSD representing power spectral density of current fluctuations. Notice here that time is normalized by product of gyromagnetic ratio and magnetization saturation γM_s. For the uniaxial anisotropy case, $\varepsilon=\frac{E}{M_sH_cV}=\frac{1}{2}\sin^2\theta$ and the magnetization dynamics has rotational symmetry due to $\frac{\partial\varepsilon}{\partial\varphi}=0$. Dynamics of the magnetization is essentially one dimensional,

$$d\theta=\left(-\alpha\frac{\partial\varepsilon}{\partial\theta}+\frac{\delta}{\tan\theta}+\beta_0\sin\theta\right)dt + \sqrt{2\delta_I}\sin\theta\xi_3\sqrt{dt}+\sqrt{2\delta}\xi_1\sqrt{dt}. \quad (3)$$

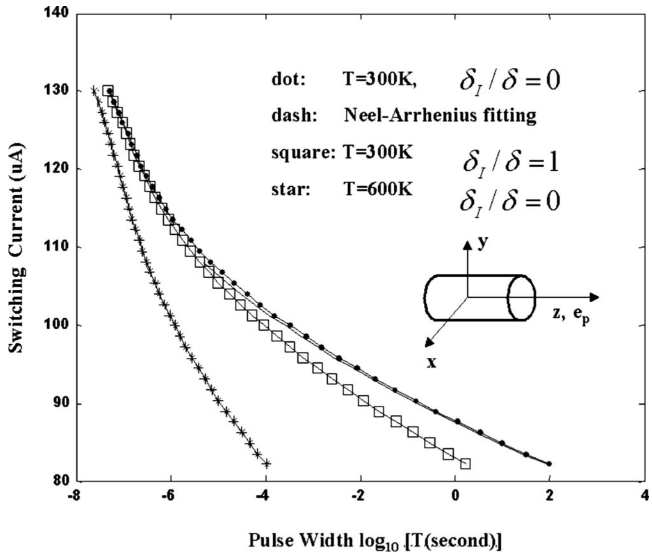

FIG. 3. Critical switching current versus dc pulse duration for a uniaxial magnetic element.

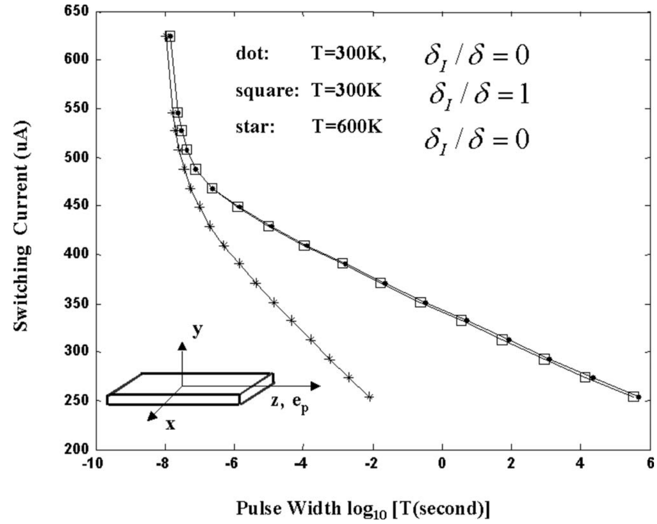

FIG. 4. Critical switching current versus dc pulse duration for a magnetic thin-film element.

Notice that even in the rotational symmetric case (3), noisy current effects on magnetization switching could not be simply treated as the temperature increases because of the $\sin\theta$ factor in the term $\sqrt{2\delta_I}\sin\theta\xi_3\sqrt{dt}$. Here $\sin\theta$ factor exists in the current fluctuation term because only current magnitude fluctuates (polarization direction is fixed by polarization layer magnetization) while both magnitude and direction of thermal magnetic field fluctuate. However, if we neglect $\sin\theta$ factor in the current fluctuation term, the total fluctuations can be written as a summation of the thermal fluctuation and the current fluctuation,

$$\delta=\delta_T+\delta_I=\frac{\alpha\gamma k_B T}{M_s^2 V}+\frac{1}{4M_s}\left(\frac{\eta\gamma h}{eM_s V}\right)^2\text{PSD}. \qquad (4)$$

Formula (4) is the same as Eqs. (8) and (9) in Ref 6 and it was used to analyze noisy current as an effective temperature rising in Ref 6.

We consider a uniaxial anisotropy magnetic element with coercivity $H_c=500$ Oe and magnetic moment $M_sV=2.56\times10^{-14}$ emu at room temperature $T=300$ K. For damping parameter $\alpha=0.02$ and polarization efficiency $\eta=0.57$, a noisy current spectral density $\text{PSD}=10^{-19}$ C^2/s gives $\frac{\delta_I}{\delta}\approx1$. Figure 3 shows critical switching current magnitude versus dc pulse width. The black dot curve is the solution of Eq. (3) at room temperature without noisy current. This solution can be fitted well to the Néel-Arrhenius formula at long-time scale (dash curve),

$$\alpha\gamma H_c t=\sqrt{\frac{\pi\delta}{2}}\frac{1}{\left(1-\frac{\alpha\eta hI}{2eM_sH_cV}\right)^2\left(1+\frac{\alpha\eta hI}{2eM_sH_cV}\right)}\times e^{1/2\delta(1-\alpha\eta hI/2eM_sH_cV)^2}. \qquad (5)$$

The square curve is the solution of Eq. (3) at room temperature with a noisy current magnitude $\frac{\delta_I}{\delta}=1$. The effect of noisy currents on accelerating magnetization switching is obvious. Figure 1 also shows the solution of Eq. (3) at 600 K temperature with $\frac{\delta_I}{\delta}=0$. This is the star curve and corresponds to neglecting $\sin\theta$ factor in current fluctuation term for a noisy current magnitude $\frac{\delta_I}{\delta}=1$ at room temperature $T=300$ K (effective temperature approach). It is clear that neglecting $\sin\theta$ factor or an effective temperature approach significantly overestimates noisy current effect on accelerating magnetization switching.

In the case of a thin-film element in MTJ, spin polarization points in the direction of the easy axis of the rectangular element $\vec{p}=\vec{e}_z$. The energy of the magnetic system is $\varepsilon=\frac{E}{M_s^2V}=\frac{1}{2}N_xm_x^2+\frac{1}{2}N_y^2m_y^2+\frac{1}{2}N_zm_z^2$, where N_x, N_y, and N_z are demagnetization factors. For a thin-film element, the perpendicular demagnetization factor is much stronger than the surface demagnetization factor $(N_y\gg N_x,N_z)$, rotational symmetry is broken and two-dimensional stochastic differential Eq. (2) with $\frac{\partial\varepsilon}{\partial\varphi}\neq0$ needs to be solved for magnetization dynamics. In order to examine explicitly the interaction between noisy current and unsymmetric magnetization dynamics, we simplify the above two-dimensional stochastic differential Eq. (2) to a one-dimensional system based on small damping approximation. For small damping parameter, a stochastic average technique[8] allows Eq. (2) to be integrated around constant energy levels to obtain the following one-dimensional stochastic differential equation:

$$d\varepsilon=\overline{A(\varepsilon)}dt+\sqrt{\overline{B(\varepsilon)}}dW(t), \qquad (6)$$

where $\overline{A(\varepsilon)}$ and $\overline{B(\varepsilon)}$ are the deterministic and stochastic terms, respectively. $dW(t)$ is the increment of a standard Brownian process. $\overline{A(\varepsilon)}$ term can be explicitly written as

$$\overline{A(\varepsilon)} = \frac{\oint d\varphi \frac{\sin\theta}{\frac{\partial\varepsilon}{\partial\theta}} \left\{ -\alpha\left[\left(\frac{\partial\varepsilon}{\partial\theta}\right)^2 + \frac{1}{\sin^2\theta}\left(\frac{\partial\varepsilon}{\partial\varphi}\right)^2\right] + \beta_0 \sin\theta\frac{\partial\varepsilon}{\partial\theta} + \delta\left(\frac{\partial^2\varepsilon}{\partial\theta^2} + \frac{1}{\sin^2\theta}\frac{\partial^2\varepsilon}{\partial\varphi^2}\right) + \frac{\delta\left(\frac{\partial\varepsilon}{\partial\theta}\right)}{\tan\theta} + \delta_I\left(\frac{\partial^2\varepsilon}{\partial\theta^2}\right)\sin^2\theta \right\}}{\oint d\varphi \frac{\sin\theta}{\frac{\partial\varepsilon}{\partial\theta}}}, \quad (7)$$

where θ and φ are magnetization angles in spherical coordinates. $\oint$ is the integration of gyromagnetic motion around a constant energy level $\varepsilon(\theta,\varphi)=\varepsilon$. $\overline{B(\varepsilon)}$ term can be explicitly written as

$$\overline{B(\varepsilon)} = \frac{\oint d\varphi \frac{\sin\theta}{\frac{\partial\varepsilon}{\partial\theta}} \left\{ 2\delta\left[\left(\frac{\partial\varepsilon}{\partial\theta}\right)^2 + \frac{1}{\sin^2\theta}\left(\frac{\partial\varepsilon}{\partial\varphi}\right)^2\right] + 2\delta_I\left(\frac{\partial\varepsilon}{\partial\theta}\right)^2\sin^2\theta \right\}}{\oint d\varphi \frac{\sin\theta}{\frac{\partial\varepsilon}{\partial\theta}}}. \quad (8)$$

Notice that the stochastic term (8) has a thermal term $2\delta[(\frac{\partial\varepsilon}{\partial\theta})^2+\frac{1}{\sin^2\theta}(\frac{\partial\varepsilon}{\partial\varphi})^2]$ and a current fluctuation term $2\delta_I(\frac{\partial\varepsilon}{\partial\theta})^2\sin^2\theta$. Only for rotational symmetric magnetization dynamic case, $\frac{\partial\varepsilon}{\partial\varphi}$ is equal to zero and the current fluctuation term could be written as an effective temperature rising format (of course $\sin\theta$ term still needs to be neglected). However, in the case of a MTJ thin film, due to strong out-of-plane demagnetization factor, the magnetization dynamics is quite unsymmetric and the current fluctuation effect is quite different from a temperature rising effect.

Figure 4 shows the critical switching current vs dc pulse duration for a magnetic thin-film element. The thin film is 160 nm long, 80 nm wide, and 2 nm thick. Magnetization saturation is 1000 emu/cc (corresponding to the magnetic moment of 2.56×10^{-14} emu). The damping parameter is 0.0057 and the polarization efficiency is 0.57. The black dot curve is switching at room temperature $T=300$ K without noisy current. The star curve is magnetization switching at increased temperature $T=600$ K. The square curve is magnetization switching at room temperature with a noisy current magnitude $\frac{\delta_I}{\delta}=1$. It is clear that for a magnetic thin-film, noisy current effects on magnetization switching are quite different than that of the temperature rising. Figure 4 shows no obvious effects of magnetization switching acceleration due to noisy current for a magnetic thin film, consistent with experiment measurement.

We have shown that noisy current effect on accelerating magnetization switching is quite different for a magnetic thin film without rotational symmetry and a uniaxial magnetic element with rotational symmetry. This is due to the interaction between magnetization dynamics symmetry and fluctuations of the system. The model result of a magnetic system without rotational symmetry is consistent with experimental measurement on MTJ thin film. However, the prediction of a magnetic system with rotational symmetry could only be tested on perpendicular anisotropy MTJ with magnetization pointing in the perpendicular direction. Currently, MTJ with high perpendicular anisotropy and perpendicular magnetization are in active research for their potential benefits in lowering switching current and maintaining thermal stability at the same time.[9]

IV. CONCLUSION

Noisy current effects on spin-torque-induced magnetization switching are studied using both models and experiment measurements. Although drastic magnetization switching acceleration due to noisy current has been predicted for a uniaxial anisotropy element, both experiment measurement and model show no obvious effect of noisy current on magnetization switching speed of a thin-film element. This difference between a uniaxial anisotropy element and a thin-film element is due to the fact that the efficiency of accelerating magnetization reversal by noisy current strongly depends on the symmetry of magnetization dynamics. Our study shows that treating noisy current as an effective temperature rising in magnetization reversal in general significantly overestimates current fluctuation effects. Understanding the interaction between magnetization dynamics symmetry and system fluctuations are critical for predicting switching behavior of spin-torque excited magnetic system with noise.

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