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1/*f*-type noise in a biased current perpendicular to the plane spin valve: A numerical study

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We add the spin momentum-transfer torque to the stochastic Landau–Lifshitz equation and use it to study the noise spectrum as a function of the current and easy axis field for configurations close to equilibrium. The current perpendicular to the plane structure is biased by a constant field perpendicular to the polarization axis of the pinned layer. We show that this structure can exhibit large 1/*f*-type noise for frequencies in the microwave regime. This 1/*f* noise is not due to the spin torque. The spin torque can only change the amplitude of the noise. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1851426]

It is very well established that a current in a spin valve can be used to control the dynamics of the magnetization in one of the layers in a current perpendicular to the plane (CPP) device by transferring angular momentum from other layers.[1–4] In magnetic recording, this additional property may not be desirable for diverse reasons. It has recently been found that CPP structures can show unwanted behavior[5] which may be detrimental to a giant magnetoresistance (GMR) signal. These latter measurements show that in the presence of a current, a sizeable amount of noise is detected in the microwave regime and below for certain configurations of the CPP valve. This behavior was attributed to spin momentum transfer since the magnitude of noise showed dependency on the sign of the current. Theoretical studies[6,7] also showed that spin momentum transfer can induce random switching in a spin valve.

In this paper we study numerically the effect of current in these structures when they are biased by an in-plane field which has a large component perpendicular to the magnetization of the thick layer. This configuration has been studied experimentally in Ref. 5. Here we model a similar structure using the stochastic Landau–Lifshitz–Gilbert (LLG) equation with and without the spin momentum term. The use of LLG with the spin torque for nonhomogeneous magnetic systems is not well justified. A satisfactory theory that takes into account nonuniformities does not exist yet.

The CPP structure has two layers, one is very thick and pinned while the other one is thin and free to precess under the influence of current or an external field. This structure is important because of its potential use in recording devices. Hence it is important to study its stability under various conditions.

It has been observed in Ref. 5 that current in a biased spin valve can give rise to 1/*f*-type noise even at relatively high frequencies, i.e., in the megahertz range for a device with a ferromagnetic resonance (FMR) frequency of the order of 10 GHz. Frequencies in this range may interfere with designs of recording heads and hence the need to understand any potential source for this noise. Since the current is perpendicular to the plane, it is natural to ask if spin momentum has a role to play in the generation of this noise. For example, Ref. 7 considers this scenario and attributes the noise to spin momentum transfer. However, this scenario does not explain the trends measured in Ref. 5.

The numerical simulation uses the LLG equation with a random white Gaussian field **h** that simulates thermal fluctuations at $T=100\ ^\circ\mathrm{C}$. The damping constant α is taken to be 0.020–0.025. The use of this damping and noise term is well justified only at temperatures below the Curie temperature and for situations where the dynamic is adiabatic and close to equilibrium.[8] All these conditions are approximately met in our experiment. The mesh size has been varied between $2\times 2\ \mathrm{nm}^2$ and $15\times 15\ \mathrm{nm}^2$; however, all the results presented here were carried out at $10\times 10\ \mathrm{nm}^2$. Below the $2\times 2\text{-nm}^2$ mesh, deviations in the transfer curve of resistance versus current become apparent at zero temperature. These deviations were mostly attributed to the spin transfer torque rather than the exchange. At finite temperature, these deviations are more pronounced and hence we avoided any comparable mesh sizes in the simulations. For the exchange term, the continuum approximation has been avoided and no attempt has been made to self-consistently renormalize the exchange with the mesh size. It should be pointed out that the spin torque is also expected to depend on the exchange constant, the mesh size, and the thickness of the film. However, since the polarization parameter p is unknown, we will ignore these difficulties. In the presence of spin torque, the LLG equation takes the following form:

$$\frac{d\mathbf{m}}{dt} = -\gamma\mathbf{m}\times\left[\mathbf{H}_{\mathrm{eff}}+\alpha\mathbf{m}\times\left(\frac{d\mathbf{m}}{dt}\right)+\mathbf{h}\right]+a\frac{pI}{d}\mathbf{m}\times(\mathbf{m}_p\times\mathbf{m}),$$

where $\mathbf{m}$ is the normalized magnetization of the free layer with thickness d and $\mathbf{m}_p$ is the local direction of the magnetization in the 'pinned' layer. The current I is taken positive when it flows from the pinned layer to the free layer. p is the polarization coefficient which is taken to be 0.5 in this study and a is a geometrical factor. The random field **h** satisfies the usual simplest correlation functions which are assumed inde-

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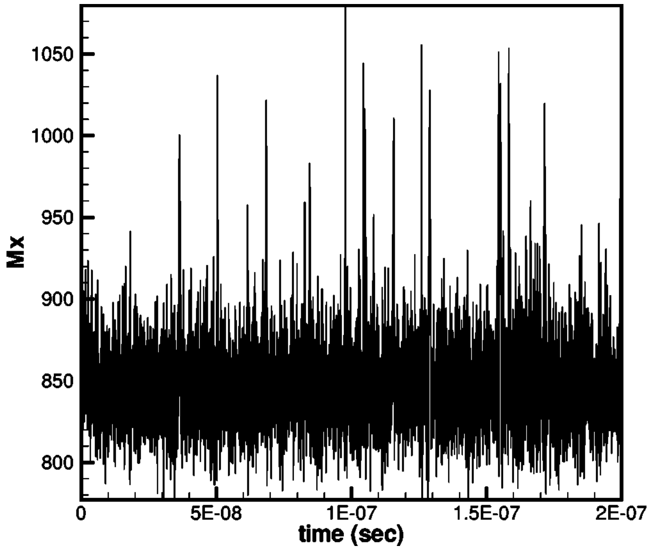

FIG. 1. The magnetization component parallel to the polarization axis, i.e., the easy axis (or x axis) as a function of time. $h_x=90$ Oe, $h_y=300$ Oe, and $I=5$ mA.

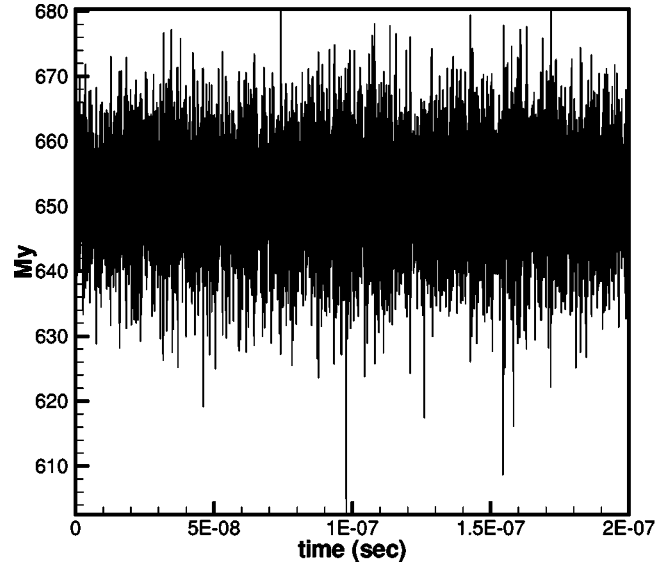

FIG. 2. The magnetization component along the direction perpendicular to the polarization axis of the current. $h_x=90$ Oe, $h_y=300$ Oe, and $I=5$ mA.

pendent of the current and the ellipticity of the precession

$$\langle h_i(t)h_j(t')\rangle = 2\alpha k_B T\delta_{ij}\delta(t-t').$$

In the actual experiment, the structure of the spin valve is somewhat more complicated than a simple pinned layer and a free layer. However, the noise measurements were carried out in a region where only the free layer is sensitive to the external bias field. Hence in the following, we assume a pinned layer and apply the bias field to the free layer. The magnetization of the pinned layer is kept fixed in plane along the easy axis which is assumed to have a uniaxial anisotropy of 50 Oe. The bias field has a constant hard axis component of 300 Oe but a variable easy axis component. This latter component will be swept between −200 and 200 Oe which happens to be the region where most of the $1/f$-type noise is detected in the simulation as well as in the experiment. It should be stressed that in all the measurements the current is believed to be below the critical current for switching. This is an important difference with previous works where noise has been detected in the switching process.

The single-particle studies do not show the noise which was observed in the experiments and hence it was soon realized that the inhomogenous configuration of the magnetization should play a fundamental role in the generation of this noise. The single-particle simulation shows smooth R-H curves; however, because of the hard axis bias field the micromagnetic simulations show curves which are not smooth, i.e., they have discontinuous slope. The discontinuity in the slopes is dependent on the magnitude of the current but not on its direction. Hence it is clear that the oersted field plays a role in the structure of these transfer curves. The measured GMR in the original experiment is believed to be a measure of the x component of the magnetization in the free layer. Hence, any detected noise is related to fluctuations in this component

$$C_{xx}(\omega) = \int d\tau\langle m_x(t+\tau)m_x(t)\rangle \exp[-i\omega\tau].$$

In the simulations, we can measure the noise in any component. We found that the noise is largest in the x component for easy axis fields around zero but it is largest in the y component for large easy axis fields; this agrees with the experiment. In Figs. 1 and 2, we show a real time trace of the magnetization components m_x and m_y very close to one of the discontinuities in the slope of the R-H curve. We see in this case that the fluctuation is largest for the x component ($M_s=1440$ emu/cc). They are negligible for the out-of plane component, the z component (not shown). Figure 1 clearly shows that the magnetization is switching between two states that differ only in the easy axis component. The switching seems to be thermally activated and not due to spin momentum transfer. This is the main point of the numerical simula-

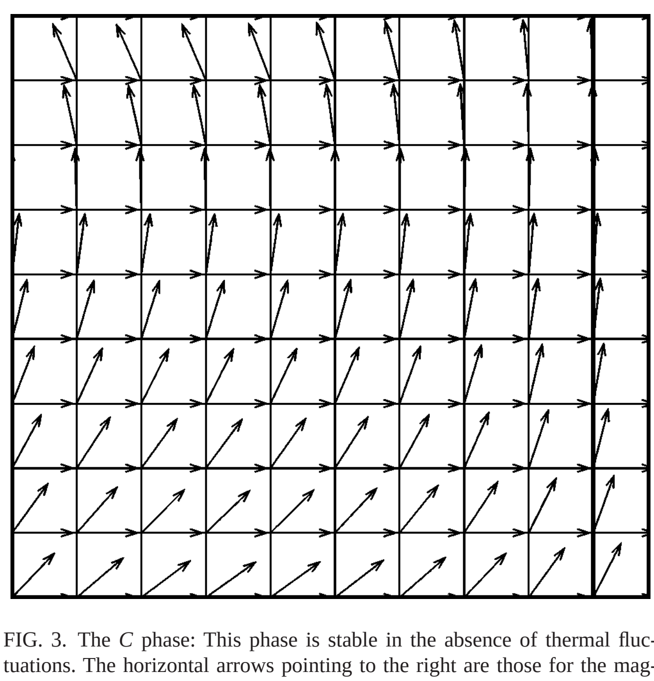

FIG. 3. The C phase: This phase is stable in the absence of thermal fluctuations. The horizontal arrows pointing to the right are those for the magnetization of the pinned layer. This configuartion is for $h_x=90$ Oe, $h_y=300$ Oe, and $I=5$ mA.

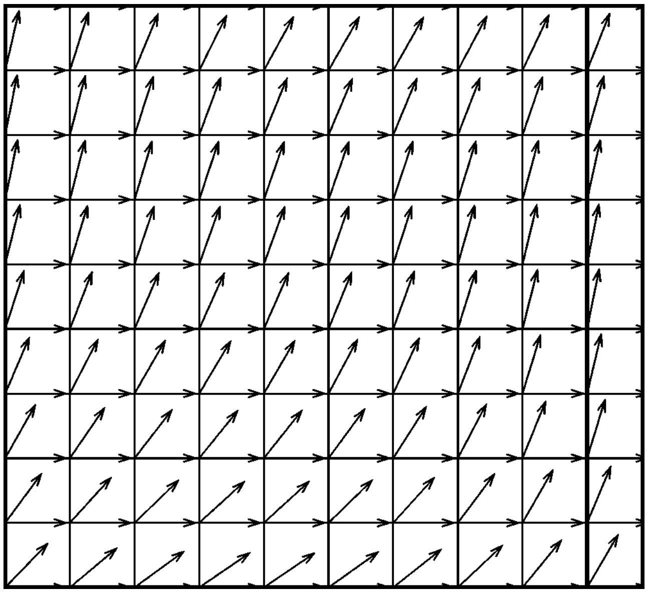

FIG. 4. The *S* phase with slightly higher bias field than for the *C* phase. h_x=110 Oe, h_y=300 Oe, and I=5 mA.

tions. The spin torque, however, tends to make one of the states more or less stable than the other. To further check this point, we show in Figs. 3 and 4 two stable configurations of the magnetization which are very close in energy. In fact, we find that the difference in energy, $|E_{90}-E_{110}|\approx 2k_BT$, is of the order of the thermal fluctuations in the system. Finally, in Figs. 5 and 6 we show that the turning off the spin momentum torque in the LLG equation does not affect the $1/f$-type noise which is another indication that the origin of this noise is mainly due to the balance between the bias field and the oersted field. Similar simulations without a hard axis field do not show this excessive noise. Depending on the relative directions of the oersted field and the bias field, the spin

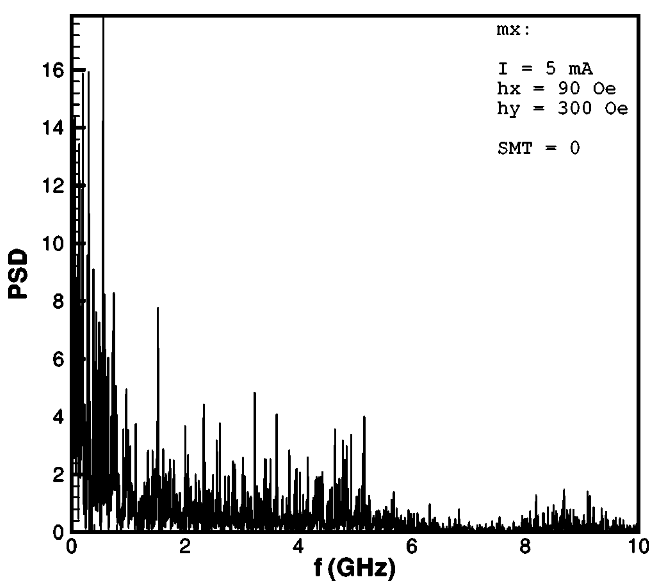

FIG. 5. The power spectrum density (PSD) in the *Mx* component with the spin torque set to zero in the LLG equation.

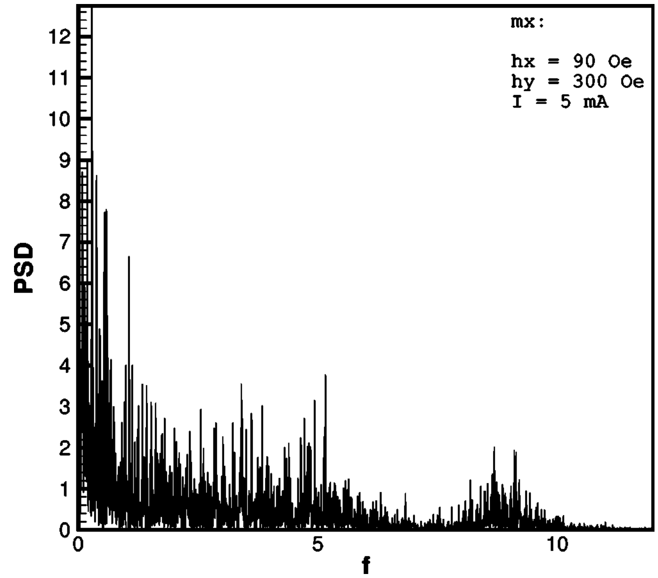

FIG. 6. The PSD in the *Mx* component using the LLG equation with a spin torque term. Same scale as in Fig. 6.

momentum torque can amplify or slightly suppress the noise in these configurations. Figures 5 and 6 show one configuration where the spin momentum transfer acts to stabilize the *C* phase. This shows that a detailed knowledge of the phase diagram of the CPP system is required when it comes to the study of noise. The simulations show, as in the experiment, that the higher the current, the larger the easy axis field at which we observe the most noise. This can be easily understood from Fig. 1 and the curling of the magnetization due to the oersted field. In fact, at much higher currents, e.g., for $I>40$ mA, the oersted field dominates and the magnetization assumes a vortex configuration. This latter configuration has no $1/f$ noise. The simulations also show that the state with (h_x=90 Oe, I=5 mA) is about twice noisier than the state with (h_x=90 Oe, I=−5 mA). This relative value is, however, much smaller than those measured in the experiment. It is suspected that the field from the leads is also a contributing factor to the noise.

In conclusion, we have shown that in spin valves with bias fields almost perpendicular to the polarization axis, the magnetization becomes highly nonuniform in the presence of the field from the current. Because of thermal fluctuations, the configuration of the magnetization may show transitions between two configurations. These transitions are the origin of the $1/f$-type noise and not the spin momentum transfer.

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