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Symmetry ensemble theory of the spin wave emitting effect driven by current in nanoscale magnetic multilayers*

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This paper proposes a symmetry ensemble model for the magnetic dynamics caused by spin transfer torque in nanoscale pseudo-spin-valves, in which individual spin moments in the free layer are considered as subsystems to form a spinor ensemble. The magnetization dynamics equation of the ensemble was developed. By analytically investigating the equation, many magnetization dynamics properties excited by polarized current reported in experiments, such as double spin wave modes and the abrupt frequency jump, can be successfully explained. It is pointed out that an external field is not necessary for spin wave emitting (SWE) and a novel perpendicular configuration structure can provide much higher SWE efficiency in zero magnetic field.

Keywords: symmetry ensemble model, spin wave emitting, spin transfer torque, nanoscale magnetic multilayer

PACC: 7225, 7360

1. Introduction

The spin wave emitting (SWE) effect,[1−4] caused by spin polarized current passing through a nanoscale magnetic multilayer structure, has been the cause of much effort devoted to the current induced magnetic switching (CIMS) effect[5−10] recently, because it can be applied in new devices, for example, microwave sources. The spin transfer torque (STT) in the nanoscale magnetic multilayer excites the spin dynamics and generates a stable radio frequency signal arising from differential resistance of the magnetic multilayer that could not be achieved with a magnetic field alone.[11,12] In typical pseudo-spin-valve (PSV) structures where the free layer and the fixed layer are initially collinearly magnetized, the steady precession requires a large external magnetic field and the emitting microwave power is small, which is not suitable for practical applications. Experimentally, it has recently been shown that a pillar-shaped PSV with the magnetization of the fixed layer being pinned perpendicularly to the easy axis of the free layer shows much higher SWE efficiency in zero external field.[13]

In the present paper, we develop a symmetry ensemble model based on quantum thoughts to investigate the magnetization dynamics properties of STT devices, which provides a method different from existing macroscopic models. Most of the macrospin[1,4] models and all of the micromagnetic models[2,3] for SWE rely on numerical simulation currently, whereas we focus on analytic solutions, which allow us to understand the underlying physical mechanism and find out the influence of various parameters on device performance. The model can successfully describe many magnetization dynamics properties excited by polarized current, such as the dependence of the excitation frequency on current, double spin wave modes and the abrupt frequency jump. Particularly, the low emitting efficiency and the dependence on high external field in collinear PSV were explained. The noncollinear configuration generates nonzero transverse spin accumulation which is necessary to SWE. We predicted that the optimal SWE efficiency would be achieved in zero

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external field by adopting the perpendicular magnetization configuration of the fixed and free layer.

2. Model description

We consider a PSV structure consisting of a fixed magnetic (thick) layer, a nonmagnetic spacer layer and a free magnetic (thin) layer. The $y-z$ plane is the easy plane for magnetization and the z axis is the easy axis in the free layer. The current is reckoned positive when electrons flow from the free layer to the fixed layer (from $+x$ to $-x$).

In our model, we considered the individual spin moments in the free layer as subsystems to form a quantum system or a spinor ensemble. The magnetization components of the subsystems are certain in the longitudinal direction (easy axis); however, they are random in the transverse plane (perpendicular to easy axis). For simplicity, let each subsystem in precession has the spin moment $\mu_{\rm B}$ (Bohr magnetron) with equal cone angle θ, but different azimuth angle φ. The magnetization of the system is denoted by $\boldsymbol{m}$. The modulus square $m_{\rm s}^2$ $(= m_x^2 + m_y^2 + m_z^2)$ of the spinor ensemble is assumed to be constant. Initially, for the system including thousands of such subsystems, the transverse magnetization components of the subsystems can be assumed to symmetrically distribute in the space and their mean value is zero, i.e., the transverse magnetization component of the system is zero, which is the reason why the theory was called the symmetry ensemble model. When a spin polarized current passes through the free layer and the magnetization directions between the fixed and free layers are noncollinear, the symmetry may be broken and the transverse magnetization component of the system is not zero any more. The oscillation of transverse component will result in a change of the longitudinal component and produces CIMS or SWE.

Although the free layer is considered as a single homogeneous magnet in our model, its magnetization is not regarded as a single vector which can take arbitrary direction in space. However, according to macrospin models, the magnetization of the free layer is a classical vector with direction and magnitude. This is the most important difference between symmetry ensemble model and macrospin models.[1,4,7,8]

The magnetic dynamic equation of the ensemble can be obtained by summation of the modified Landau–Lifshitz–Gilbert (LLG) equations of all the subsystems.

$$\begin{aligned} V\frac{{\rm d}\boldsymbol{m}}{{\rm d}t} =& \frac{\rm d}{{\rm d}t}\sum\nolimits_i \boldsymbol{m}_i \\ =& -\sum\nolimits_i \left[\gamma \boldsymbol{m}_i \times \boldsymbol{H}_{\rm eff} - \alpha \boldsymbol{m}_i \times \frac{{\rm d}\boldsymbol{m}_i}{{\rm d}t}\right] + \boldsymbol{\Gamma}_{\rm I}, \\ \boldsymbol{H}_{\rm eff} =& \boldsymbol{H}_{\rm app} + \boldsymbol{H}_{\rm an} + \boldsymbol{H}_{\rm d} \\ =& \boldsymbol{H}_{\rm app} + \beta m_z \hat{\boldsymbol{z}} - 4\pi m_x \hat{\boldsymbol{x}}, \end{aligned} \tag{1}$$

where $\boldsymbol{H}_{\rm eff}$, $\boldsymbol{H}_{\rm app}$, $\boldsymbol{H}_{\rm an}$ and $\boldsymbol{H}_{\rm d}$ are the effective field, external magnetic field along $\hat{\boldsymbol{z}}$ direction, anisotropy field in which β represents its intensity, and demagnetization field, respectively, α and γ are the Gilbert damping constant and gyromagnetic ratio, respectively, $\boldsymbol{m}_i$ represents a spin moment with index i and Σ_i involves all of the spins in the free layer.

The second term on the left of Eq.(1) is the STT caused by spin accumulation in the free layer, which is the difference between the spin currents flowing into and out of the free layer. Therefore, the STT can be expressed as,

$$\boldsymbol{\Gamma}_{\rm I} = -\frac{\gamma\hbar}{2V}\Delta\eta \boldsymbol{I}\hat{\boldsymbol{M}}, \tag{2}$$

where $\hat{\boldsymbol{M}}$ is the unit vector of fixed layer magnetization, $\boldsymbol{I}$ is the electric current and $\Delta\eta$ is the difference between spin current polarizations at the injection and extraction interfaces of the free layer. According to the spin transport equations for the two-current model[14] and the continuous conditions of spin currents and the difference of the chemical potentials for the spin majority and minority at the two interfaces, the spin current polarization at the injection interface approximately equals $(\eta_1+\eta_2)/2$, while at the extraction interface it equals $\eta_2/2$, where η_1 and η_2 are the spin polarization factors of the fixed layer and free layer, respectively.[15] Thus, $\Delta\eta$ approximately equals to $\eta_1/2$. Fortunately, $\Delta\eta$ is nearly independent of the free layer's magnetization, which significantly simplifies the treatment for the problem.

The SWE and CIMS effects are both caused by STT in similar magnetic configurations, so it is naturally necessary to figure out the relation between SWE and CIMS. The angle between $\hat{\boldsymbol{M}}$ and $\hat{\boldsymbol{z}}$ denoted by θ_0, satisfies $\cos\theta_0 = \hat{\boldsymbol{M}}\cdot\hat{\boldsymbol{z}}$. For simplicity, we suppose that the transverse component of the STT is within the film plane and along y direction. Therefore, it can be decomposed into two orthogonal components:

$$\begin{aligned} \Gamma_{\perp} &= \frac{\gamma\hbar\eta_1}{4V} I \sin\theta_0 \hat{y}, \\ \Gamma_{||} &= \frac{\gamma\hbar\eta_1}{4V} I \cos\theta_0 \hat{z}. \end{aligned} \tag{3}$$

These two orthogonal components play different roles. The longitudinal component acts as a negative damping counteracting Gilbert damping and results in a metastable state of the free layer. As the longitudinal damping is overcome, the CIMS effect occurs. The transverse component generates an oscillation of transverse magnetization of the free layer. Because the modulus square $m_{\rm s}^2$ is constant, the magnitude of the longitudinal magnetization changes with time synchronously, which leads to the SWE effect. The details will be described in the next section.

3. Equation of solutions

The first-order approximation of the LLG equation is

$$\begin{aligned} V\frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t} =& -\sum\nolimits_i [\gamma \boldsymbol{m}_i \times (\boldsymbol{H}_{\rm eff} + \boldsymbol{H}_{\rm I}) \\ & - \gamma\alpha \hat{\boldsymbol{m}}_i \times (\boldsymbol{m}_i \times \boldsymbol{H}_{\rm eff})] \\ & - \frac{\gamma\hbar\eta_1 I}{4} \hat{\boldsymbol{M}}, \end{aligned} \tag{4}$$

where the current induced effective field $\boldsymbol{H}_{\rm I}$ comes from the damping $\Gamma_{\rm stt}$ related to STT

$$\boldsymbol{\Gamma}_{\rm stt} = \eta_1\alpha\gamma\frac{\hbar I}{4V}\hat{\boldsymbol{m}} \times \hat{\boldsymbol{M}} = -\gamma \boldsymbol{m} \times \boldsymbol{H}_{\rm I}, \tag{5}$$

i.e.

$$\boldsymbol{H}_{\rm I} = -\eta_1\alpha\frac{\hbar I}{4V m_{\rm s}}\hat{\boldsymbol{M}}. \tag{6}$$

Compared with the precession term of LLG equation, we can conveniently take the current induced damping torque Eq.(5) as a part of contribution to the effective field because the electric current is a macroscopic physical quantity and independent of the free layer magnetization $\boldsymbol{m}$.

In order to discover the movements of transverse and longitudinal components, the analytical solution of Eq.(4) is helpful. The free layer magnetization $\boldsymbol{m}$ is decomposed into the longitudinal (parallel to $\hat{\boldsymbol{z}}$) and transverse (perpendicular to $\hat{\boldsymbol{z}}$) components denoted by m_z and m_φ, respectively. The transverse component is defined as $m_\varphi = m_x + im_y$. After summation over all spins i in Eq.(4), the equation of the longitudinal component is

$$\begin{aligned} \frac{\mathrm{d}m_z}{\mathrm{d}t} =& \frac{\gamma\alpha\hbar\eta_1 I \sin\theta_0 < m_\varphi >}{4V m_{\rm s}} \\ & + \gamma\alpha \left(H_{\rm eff} + 2\pi m_z\right) m_{\rm s} \left(\frac{m_\varphi^2}{m_{\rm s}^2}\right) \\ & - \frac{\gamma\hbar\eta_1 I \cos\theta_0}{4V}, \end{aligned} \tag{7}$$

where $< m_\varphi >$ is the average of the subsystems' transverse components with respect to the azimuthal angle φ.

For the initial state without the polarized current, $< m_\varphi >$ is zero according to the symmetry ensemble model. When the transverse spin accumulation breaks the symmetry of the system, the average transverse magnetization is not zero any more, but the term with φ can still be neglected since the damping constant is very small (0.01–0.05). In a steady state, we can estimate the critical electric current by setting the time derivative to be zero.

The dynamic equations of transverse components are

$$\begin{aligned} \frac{\mathrm{d}m_x}{\mathrm{d}t} =& -\gamma H_z m_y - \frac{\gamma\alpha m_z B_z}{m_{\rm s}} m_x, \\ \frac{\mathrm{d}m_y}{\mathrm{d}t} =& \gamma B_z m_x - \frac{\gamma\alpha m_z H_z}{m_{\rm s}} m_y - \frac{\gamma\hbar\eta_1 I \sin\theta_0}{4V}, \end{aligned} \tag{8}$$

where $B_z = H_z + 4\pi m_z$. The terms involving α in Eq.(8) could be neglected and the equations were simplified as

$$\frac{\mathrm{d}\tilde{m}_\varphi}{\mathrm{d}t} = \mathrm{i}\omega_0 \left(\tilde{m}_\varphi - m_0\right), \quad \omega_0 = \gamma \left(H_z B_z\right)^{1/2}, \tag{9}$$

where ω_0 is the precession frequency. The initial conditions

$$\tilde{m}_\varphi|_{t=0} = 0 \quad \text{and} \quad \mathrm{d}\tilde{m}_\varphi/\mathrm{d}t|_{t=0} = \gamma\hbar\eta_1 I \sin\theta_0/4V$$

lead to the solution

$$\begin{aligned} \tilde{m}_\varphi =& m_0 \left[1 - \exp\left(\mathrm{i}\omega_0 t\right)\right] \\ =& m_0 \exp\left(\mathrm{i}\omega_0 t\right) \sin\left(\omega_0 t/2\right), \end{aligned} \tag{10}$$

where $m_0 = \gamma\hbar\eta_1 I \sin\theta_0/4\omega_0 V$, $\tilde{m}_\varphi = \tilde{m}_x + \mathrm{i}m_y$ and $\tilde{m}_x = \left(B_z/H_{\rm eff}\right)^{1/2} m_x$. To recover m_φ, the transverse component solution is rewritten as

$$\begin{aligned} m_\varphi =& m_x + \mathrm{i}m_y \\ =& m_0 \left[\left(\frac{H_z}{B_z}\right)^{1/2} (1 - \cos\varphi) - \mathrm{i}\sin\varphi\right]. \end{aligned} \tag{11}$$

4. Results and discussions

4.1. Precession trajectory

Under normal temperature, the trajectory of the system is an ellipse tangent to y-axis and the precession axis (in the $x-z$ plane) tilts to x-axis when the current passes through the structure in which the magnetizations of the free and fixed layers are noncollinear (see Fig.1(a)). In general, the precession trajectories projected onto the $x-y$ plane are ellipses as shown in Fig.1(b). m_φ has a circle trajectory if $H_z = B_z$, corresponding to very big applied field. Furthermore, the mean value of m_φ is $m_0(H_z/B_z)^{1/2}$ along x axis, which should generate a precession torque that tentatively balances the transverse STT caused by the spin current.

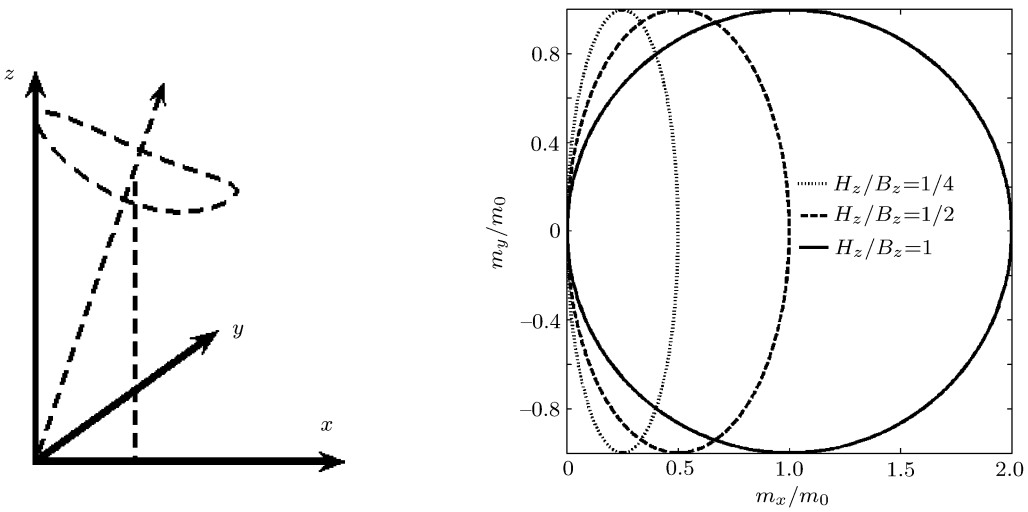


Fig.1. (a) The precession trajectory with precession axis (dashed arrow line) tilting to the x-axis. (b) The precession trajectories projected onto the $x-y$ plane.

The transverse magnetization of the system is zero when the initial magnetizations of the free and fixed layer are collinear, i.e., $\theta_0 = 0$. This collinear configuration presents zero transverse spin accumulation and the unsynchronized precession electrons have symmetrical distribution with respect to the azimuthal angle φ. Although every subsystem is precessing with frequency ω_0, the cone angle of the precession and the magnetoresistance remain constant, i.e., the microwave signal never appears. Therefore, the SWE appears only when those two requirements, the noncollinear configuration and the existence of spin current, are satisfied.

In early experiments, the initial noncollinear angle θ_0 is so small that the magnetization oscillation is rather weak and the SWE effect is not obvious in low external field. The transverse spin accumulation reaches the maximum if the magnetization of the free layer is perpendicular to that of the fixed layer, so this new perpendicular configuration has optimal SWE efficiency even without the external field. This has been experimentally demonstrated recently.[13]

4.2. Precession frequency

The quantitative relation between precession frequency and current is obtained by fitting H_z, B_z and H_I into the frequency formula for the cylindrical magnetic body. The frequency formula[16] is

$$\omega_0^2 = \gamma^2(H_z + H_\mathrm{I} + 4\pi m_z)(H_z + H_\mathrm{I}). \tag{12}$$

The current induced effective field

$$\boldsymbol{H}_\mathrm{I} = -\eta_1\alpha\frac{\hbar I}{4Vm_\mathrm{s}}\hat{\boldsymbol{M}}$$

with the opposite direction of H_z reduces the frequency, but this term could be neglected due to the very small damping constant. The frequency formula is reduced to

$$\omega_0^2 = \gamma^2\left(H_\mathrm{app} + \beta m_z + 4\pi m_z\right)\left(H_\mathrm{app} + \beta m_z\right). \tag{13}$$

The precession frequency mainly depends on the magnetic field and monotonously increases with the increase of H_app in small angle precession, and it decreases with the increase of electric current in the large angle precession because the current reduces m_z, which is consistent with experiments.[6]

4.3. Double spin wave modes

According to experimental reports,[3,11] there are two coexisting spin wave modes with different frequencies and amplitudes. A frequency jump is observed[3,11] when the oscillation intensities of the two modes vary with current and external field. These phenomena can be illustrated by the extremum analysis of the magnetization oscillation intensity as follows. From Eq.(11), the oscillation intensity of the transverse component is

$$\begin{aligned} |m_x|^2 + |m_y|^2 =& m_0^2 \left[\frac{H_z}{B_z} (1 - \cos\varphi)^2 + \sin^2\varphi \right] \\ & \propto \frac{H_z}{B_z} (1 - \cos\varphi)^2 + \sin^2\varphi. \end{aligned} \tag{14}$$

By setting the derivative of Eq.(14) to zero, the extrema are determined by $\sin\varphi = 0$ and $\cos\varphi = H_z/(H_z - B_z)$. The latter equation is useable if H_z/B_z is assumed to be less than $1/2$.

When the current is less than the critical value and the external field is small, B_z is far larger than H_z and thus the majority of the contribution to the transverse oscillation amplitude is from m_y. If $0 < H_z/B_z < 1/2$ is satisfied, the minimum points are $\varphi = 0$ or π for $\sin\varphi = 0$, while two maximum points are around $\varphi = \pi/2$ and $3\pi/2$ for $\cos\varphi = H_z/(H_z - B_z)$. The magnetoresistance oscillation frequency is $2\omega_0$ because m_z changes twice in one precession cycle. This is called the high frequency SWE mode. When $H_z/B_z > 1/2$, corresponding to very high $H_{\rm app}$, the magnetization oscillation intensity has only one minimum point $\varphi = 0$ and one maximum point $\varphi = \pi$. The majority of the contribution to the transverse oscillation amplitude is from m_x and the magnetoresistance oscillation frequency is ω_0. This is called the low frequency SWE mode. As shown in Fig.2, the bold line is the threshold line that divides the two oscillation modes. The SWE frequency changes and it is nearly doubled or halved when the threshold line is crossed. This is called the universal frequency jump in SWE.[3]

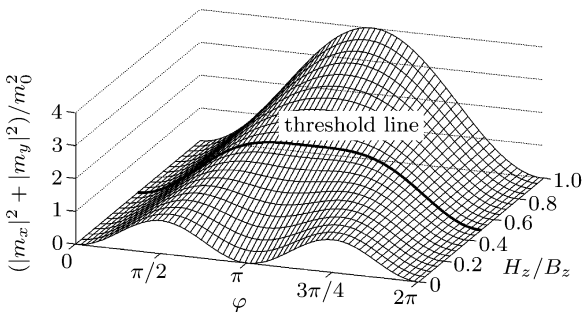


Fig.2. The normalized oscillation intensity (the bold line is the threshold line).

4.4. Comparison with experiment results

According to Eq.(8), for the metastable state of the free layer, the dependence of the current on M_z or cone angle θ could be expressed as $I = 2e\alpha[2h + (2\beta + 1)\cos\theta]V\sin^2\theta\mu_0 m_{\rm s}^2/\eta_1\hbar$ in SI units, here $h = H_{\rm app}/M_{\rm s}$. The critical current is approximately $I_{\rm c} \sim 4e\alpha(H_z + 2\pi m_z)Vm_{\rm s}/\eta_1\hbar$, which is consistent with published reports.[9] The precession frequency could be expressed as $\omega_0^2 = \omega\gamma^2\mu_0 m_{\rm s}^2[h + (\beta + 1)\cos\theta](h + \beta\cos\theta)$. The transition condition of the spin wave mode from high frequency to low frequency is $B_z/\mu_0 H_z < 2$ or $h > \cos\theta/(1 - \beta)$. The parameters used in the simulation are $\mu_0 M_{\rm s} = 0.61\,{\rm T}$, $\alpha = 0.035$, $\beta = 0.1$, $\gamma = 1.9 \times 10^{11}/{\rm T}\cdot{\rm s}$, $h = 0.5$, $V = 2 \times 10^{-23}\,{\rm m}^3$, $\eta_1 = 0.3$. Figure 3 gives the curves of frequency versus current and the ratio between spin wave oscillation amplitudes of high frequency mode and low frequency mode. The critical switching current is 2.75 mA. The SWE frequency falls with the increase of current I, and the mode transition point of the amplitudes appears at $I_t = 2.54\,{\rm mA}$ or cone angle 56°, thereafter, instead of high frequency mode, the low frequency mode becomes dominative for SWE. The simulation results

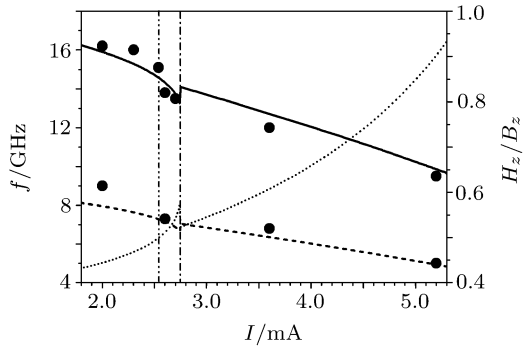


Fig.3. The spin wave frequency versus current I for high (solid line) and low (dashed line) frequency modes. The solid circles represent the experimental data extracted from Ref.[11] with permission. The dash dot line is the critical current. The dotted line shows the ratio of spin wave oscillation amplitudes for high frequency mode over low frequency mode. The dash dot dot line is the transformation current (I_t) corresponding to the frequency jump; the amplitude of high frequency is larger than that of low frequency if the current is lower than I_t, and vice versa.

are consistent with the experimental data extracted from Ref.[11]. When the current is beyond 5.5 mA (twice of I_c), the SWE disappears in experiments[11] (Fig.3 did not show), because the current is much higher than the critical current; the magnetization of the free layer is reversed and reaches saturation so that the resistance does not change any more.

5. Conclusions

A symmetry ensemble model was proposed for the magnetic dynamics in nanoscale magnetic multilayers. The modified LLG equation was analytically investigated. The model successfully described many magnetization dynamics properties excited by STT. The critical switching current obtained from the model is consistent with published reports.[9] According to the model, the SWE frequency is correlative with the magnetic field and spin current. The external field tends to increase the frequency, but the action of the spin current is rather adverse. Two oscillation modes, one in the x direction and the other in the y direction, coexist and play as the main mode under different conditions. The main mode is the y (x) direction oscillation with frequency $2\omega_0$ (ω_0) if H_z/B_z is less (larger) than 1/2. An abrupt frequency jump will occur near the threshold 1/2 of H_z/B_z by controlling the current.

The noncollinear configuration generates nonzero transverse spin accumulation and it is necessary for SWE. We predicted that the optimal SWE efficiency can be achieved by adopting the perpendicular magnetization configuration of the fixed and free layer.

References

[1] Xiao J, Zangwill A and Stiles M D 2005 *Phys. Rev.* B **72** 014446

[2] Berkov D and Gorn N 2005 *Phys. Rev.* B **71** 052403

[3] Krivorotov I N, Berkov D V, Gorn N L, Emley N C, Sankey J C, Ralpha D C and Buhrman R A 2007 *Phys. Rev.* B **76** 024418

[4] Bertotti G, Serpico C, Mayergoyz I D, Magni A, d'Aquino M and Bonin R 2005 *Phys. Rev. Lett.* **94** 127206

[5] Slonczewski J C 1996 *J. Magn. Magn. Mater.* **159** L1

[6] Berger L 1996 *Phys. Rev.* B **54** 9353

[7] Ren M, Zhang L, Hu J N, Deng N and Chen P Y 2007 *Acta Phys. Sin.* **56** 2863 (in Chinese)

[8] Zhang L, Ren M, Hu J N, Deng N and Chen P Y *Acta Phys. Sin.* **58** 488 (in Chinese)

[9] Sun J Z 2006 *IBM J. Res. & Dev.* **50** 81

[10] Stiles M D and Zangwill A 2002 *Phys. Rev.* B **66** 014407

[11] Kiselev S I, Sankey J C, Krivorotov I N, Emley N C, Schoelkopf R J, Buhrman R A and Ralph D C 2003 *Nature* **425** 380

[12] Pribiag V S, Krivorotov I N, Fuchs G D, Braganca P M, Ozatay O, Sankey J C, Ralph D C and Buhrman R A 2007 *Nature Physics* **3** 498

[13] Devolder T and Meftah A 2007 *J. Appl. Phys.* **101** 063916

[14] Fert A 1969 *J. Phys.* C **2** 1784

[15] Hu J N, Ren M, Zhang L, Deng N, Dong H and Chen P Y 2007 *Mater. Res. Soc. Symp. Proc.* **998** J02-03

[16] Kittel C 1948 *Phys. Rev.* **73** 155