Spin-torque-induced switching in a perpendicular GMR nanopillar with a soft core inside the free layer

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\textbf{Abstract.} Considerable reduction of the switching current is observed on micromagnetic simulation in a perpendicularly magnetized giant magnetoresistive (GMR) nanopillar with a soft nanocore inside the free layer. In this paper, an analytical model based on the single-domain assumption for both the hard and the soft regions is developed to deeply understand the nanocore effect. Combining the analytical solutions with the micromagnetic simulation results, we could interpret well the essential features of the spin-torque-driven magnetization switching in such GMR pillars with perpendicular anisotropy. The asymmetric critical switching current is attributed to the stray field caused by the fixed layer together with the intrinsic difference in the spin-torque efficiency associated with the current direction. However, such an asymmetric switching could be compensated partially by an asymmetric reduction in the critical current after a soft core is inserted into the free layer. In addition, a slight jump observed in the simulated antiparallel-to-parallel switching curve could also be explained by this model.
1. Introduction

Recently, considerable interest in spin-transfer torque-induced magnetization switching [1, 2] has been stimulated not only by its potential application as a novel, direct writing scheme for the nonvolatile magnetic random access memory (MRAM) but also by the further understanding of the fundamental spin-related physics. Achieving low critical switching current density ($J_c$) is one of the most challenging aspects for the reduction of power consumption and successful adaptation of the spin-transfer writing scheme to the underlying transistor of memory devices. Up to now, most efforts concerning spin-torque devices focus on the giant-magnetoresistive (GMR) devices or magnetic tunnel junctions (MTJs) in which both the free layer and the fixed layer (i.e. polarizer) have in-plane magnetization [3–10]. In such in-plane-magnetized devices, reduction of the critical switching current has been attempted by using low-saturation magnetization free layers [6], double pinned layer structures [7, 8] or nanocurrent channels (NCCs) [9, 10] to enhance the spin-torque effect. However, the in-plane magnetization of individual memory elements requires an aspect ratio (length/width) of 2 or above in order to eliminate the curling magnetization formed at the edge of the element, which limits the improvement of high-density MRAM. Moreover, with the memory cell shrinking, much higher magnetic anisotropy is required in order to keep the thermal stability.

Recent developments in nanopillars with perpendicular magnetic anisotropy show considerable promise as candidates for the spin-transfer memory applications because such ‘perpendicular’ systems are not only devoid of aspect ratio limitation but also show good thermal stability [11–15]. However, the high magnetic anisotropy in turn leads to a relatively high critical current, which has been reported in some experiments performed on the perpendicular GMR pillars. Typical $J_c$ values are 2.6–7.5 × 10$^7$ A cm$^{-2}$ for the [Co/Ni]$n$ multilayer [11, 12] and 1–1.4 × 10$^8$ A cm$^{-2}$ for the $L1_0$-FePt layer [13] and the [CoFe/Pt]$n$ multilayer [14] as the free layers. In order to reduce the switching current, Meng and Wang [16] introduced an NCC layer on top of the free layer to locally enhance the spin-torque effect, resulting in a considerable asymmetric decrease of $J_c$. The $J_c$ with NCC layer is 52% of that without NCC for the switching from parallel to antiparallel alignment (P → AP) and 31% for the opposite switching direction (AP → P). In our previous study [17], we proposed a new design with a soft nanocore inside the free layer, in which the effective anisotropy is slightly reduced but dramatically fast switching and significant $J_c$ reduction are obtained through the domain nucleation process. In addition, we observed an asymmetric reduction of $J_c$ for the free layer incorporating a soft nanocore, and the reduction of $J_c^{P\rightarrow AP}$ is much greater than that of $J_c^{AP\rightarrow P}$
for a given nanocore size. For instance, as shown in figure 1, without the nanocore ($\delta = 0$, where $\delta$ is defined as the ratio of the area of the soft core to that of the whole free layer), the critical current density ($J_c$) is reduced and the asymmetry of $J_c$ is improved after inserting the nanocore. A schematic diagram of the perpendicular GMR pillar with a soft core inside the free layer is shown in the right panel.

Figure 1. Magnetization switching loops obtained from micromagnetic simulations for a perpendicular GMR nanopillar without a nanocore and with an inserted soft nanocore of 12.5% (core size: $40 \times 30$ nm$^2$). The critical current density ($J_c$) is reduced and the asymmetry of $J_c$ is improved after inserting the nanocore. A schematic diagram of the perpendicular GMR pillar with a soft core inside the free layer is shown in the right panel.

Besides the reduction of critical current, the improvement of switching asymmetry is another important issue for the proper operation of MRAM. The observed $J_c^{P \rightarrow AP}$ is usually higher than the $J_c^{AP \rightarrow P}$, which has been clarified due to the intrinsic difference in the spin-transfer torque efficiency for the negative and positive current directions in GMR pillars [1]. Several ways to improve the switching symmetry in the in-plane [8, 18] and perpendicular [16] magnetized nanostructures have been reported previously, but the mechanism of the symmetric improvement is distinct for different systems. In the spin valve or MTJ structures with double in-plane pinned layers, the better symmetry of $J_c$ is attributed to the improvement of spin-torque angular dependence efficiency [7, 19]. For the in-plane magnetized MTJ devices, it is known that the magnitude of $J_c$ is associated with the asymmetric spin polarization of the fixed layer [20]. By introducing an NCC layer, the $J_c$ can be greatly reduced, which leads to the polarization difference between negative and positive currents getting smaller. Hence, the $J_c$ symmetry is improved. Nevertheless, for the perpendicular GMR devices containing a similar NCC layer, the improved symmetry originates from the different current confined effects between the negative and positive current flowing directions [18].

For the GMR pillars with a soft nanocore, although considerable asymmetric reduction of switching current has been predicted by simulation, the underlying physical origin of the current reduction has remained unclear. In the present paper, we perform an extensive study of the soft nanocore effect on the reduction of asymmetric critical switching current.
The paper is organized as follows. In section 2, we propose a simple model by assuming both the hard and soft regions of the free layer in single domain states. With the model, we are able to analytically predict the magnitude of critical switching current. The numerical analytical results and micromagnetic simulations are given in section 3, which could successfully interpret the physical origins of the asymmetric switching current and asymmetric reduction with the soft core. Finally, in section 4, we summarize the most interesting features of the soft nanocore design in the perpendicular spin-torque devices.

2. Analytical model

As described in our previous work [17] for a GMR nanopillar with perpendicular anisotropy, the magnetization reversal process of the free layer could be divided into two stages: the first stage is for the initial switching from the out-of-plane direction to the in-plane direction, and the second one corresponds to the subsequent switching from the in-plane direction to the final opposite perpendicular direction. The switching is mainly dominated by the competition among the perpendicular anisotropy field ($H_k$), the demagnetizing field ($H_d$) and the spin-transfer torque. The effects of $H_k$ try to maintain the free layer magnetization to be in the vertical direction, whereas $H_d$ draws it to be in-plane. Since $H_k$ is larger than $H_d$, the spin-transfer torque generated by the current is indispensable in the first switching stage in order to drive the magnetization to leave the initial perpendicular direction. To reduce the critical switching current, we introduce a soft nanocore with intrinsic in-plane anisotropy inside the perpendicular free layer, as sketched in the right panel of figure 1. The intrinsic in-plane anisotropy of the soft core could not only reduce the effective $H_k$, but also help draw the moments of the hard region to the in-plane direction through the exchange interaction. Accompanied by domain nucleation and expansion, a fast switching process with lower $J_c$ has been observed.

To gain deep insights into the physics of the $J_c$ reduction in the perpendicular nanopillar with an in-plane hard/soft composite free layer, we successfully developed an analytical model based on the macroscopic Landau–Lifshitz–Gilbert (LLG) equation including the Slonczewski spin-torque term. Strictly, Slonzewski’s model is suitable only for identical free layer and pinned layer structure and some general models have been developed for the asymmetric spin-valve structure [21, 22]. Here, we consider that the asymmetric structure would not play an important role in the obtained results, since the properties such as spin-related conductance, magnetization and spin polarization of the soft core (NiFeCo alloy) and the hard region (Co/Ni multilayer) are almost the same. Moreover, the soft area is limited to only 2–12% of the whole free layer area [17]. Therefore, the structure asymmetry induced by the soft nanocore could be neglected and Slonzewski’s model is appropriate in this study. For that, we use $M^i$ ($i = 1$ or 2) to represent the respective magnetization of the main hard region ($i = 1$) and the soft nanocore ($i = 2$). The dynamics of the free layer is governed by two coupled LLG equations:

$$\frac{dM^i}{dt} = -\gamma M^i \times H^i_{\text{eff}} - \frac{\alpha}{M^i_s} M^i \times \frac{dM^i}{dt} + \frac{\gamma a_j}{M^j_s} M^j \times (M^j \times \hat{M}_p),$$

where $H^i_{\text{eff}}$ is the effective magnetic field for the hard region ($i = 1$) and the nanocore ($i = 2$), which includes the anisotropy field and demagnetizing field. $\gamma$ is the gyromagnetic ratio and $\alpha$ is the damping constant. $M^i_s$ is the saturation magnetization of the corresponding region in the composite free layer. For simplicity, we assume that both the hard and the nanocore regions

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have the same $M_s$. $\dot{M}_p$ is the unit vector along the electron polarization direction ($+$ in this paper). $a_J$ is the spin-torque factor in the unit of magnetic field, with the following expression:

$$a_J = -\frac{\hbar}{2eM_s t} g(\theta),$$

(2)

where $g(\theta)$ is the scalar function in Slonczewski’s model [1], $t$ is the free layer thickness, and $J$ is the current density.

By assuming that both the nanocore and the main hard region are uniformly magnetized, we can explicitly write the effective magnetic field $H_{\text{eff}}$ as

$$H_{\text{eff}} = H_{k2} \frac{M_s}{M_s} \delta \mathbf{e}_x + \left( H_{k1} \frac{M_s}{M_s} (1 - \delta) - 4\pi M_z + H_s \right) \mathbf{e}_z = H_x \mathbf{e}_x + H_z \mathbf{e}_z,$$

(3)

where $\delta$ is the ratio of the area of the nanocore to that of the whole free layer, and $\mathbf{e}_x$ and $\mathbf{e}_z$ are the unit vectors of the $+x$ and $-z$ directions, respectively. $H_{k1}$ is the perpendicular anisotropy field of the hard region, $H_{k2}$ is the intrinsic in-plane anisotropy field of the nanocore region, $H_s$ is the stray field generated by the fixed layer [23, 24], and $-4\pi M_z$ is the demagnetizing field of the composite free layer. The components of the total effective field along the $x$- and $z$-directions are denoted by $H_x$ and $H_z$, respectively.

Considering that the magnetization of the perpendicular nanopillar switches along the $z$-direction, we write down only the governing equation for the $z$-component of free-layer magnetization ($M_z$) by inserting equation (3) into (1),

$$\frac{1 + \alpha^2}{\gamma} \frac{dM_z}{dt} = \left( M_y - \frac{\alpha}{M_s} M_x M_z \right) H_x + \frac{\alpha}{M_s} \left( M_x^2 + M_y^2 \right) H_z - a_J \frac{M_z}{M_s} \left( M_x^2 + M_y^2 \right).$$

(4)

Under the action of spin polarized current, the magnetization precession of the free layer in the perpendicular GMR nanopillar demonstrates a spiral trajectory of motion, especially in the first stage (i.e. from P (or AP) to the in-plane). In this stage, the change in the $z$-component of magnetization is much slower than those of the in-plane components, which can be treated as a quasi-periodic orbit. Therefore, we could take an approximation of $\langle M_z M_y \rangle = 0$ and $\langle M_x^2/(M_z^2 + M_y^2) \rangle = 1/2$ over one period (i.e. the in-plane component of magnetization rotates by 360°) [24]. Also, by taking the equilibrium condition of $\langle dM_z/dt \rangle = 0$, the required critical spin-torque factor $a_J$ can be derived:

$$a_{Jc} = \alpha \left[ H_{k1} \frac{M_z}{M_s} (1 - \delta) - 4\pi M_z + H_s \right] - \alpha M_z \frac{H_{k2}}{2M_s} \delta.$$  

(5)

Thus, the magnetization reversal for the perpendicular nanopillar occurs only when the spin-torque magnitude obtained from equation (2) is larger than the required critical torque determined by equation (5), i.e. $|a_J| > |a_{Jc}|$. Therefore, it is essential to decrease $|a_{Jc}|$ for a reduction of the critical switching current. Note that expression (5) suggests that the $|a_{Jc}|$ could be reduced by a decrease of $H_{k1}$ and an increase of $H_{k2}$. In addition, the increase in $\delta$ can also reduce the value of $|a_{Jc}|$ and hence result in lower critical switching current, which is consistent with our previous micromagnetic simulation results [17]. However, a big nanocore will cause the magnetization of the whole free layer to deviate from the perpendicular direction; one should consider the appropriate nanocore dimension without compromising the perpendicular magnetization alignment in the practical device design.
3. Numerical results and discussions

In this section, we compare the numerical solution of the analytical results with the micromagnetic simulations. The computational material parameters are chosen as follows: the anisotropy constants of the hard region and the nanocore in the composite free layer are set to be $K_1 = 3.0 \times 10^7$ erg cm$^{-3}$ and $K_2 = 1.0 \times 10^6$ erg cm$^{-3}$, respectively. The typical material with perpendicular anisotropy serving as the hard region could be the [Co/Ni]$n$ multilayer \[11\]. Generally, the thickness of the individual sublayers in the multilayer system should be very thin in order to achieve perpendicular anisotropy. Here, we suppose 0.25 and 0.55 nm for the Co and Ni layers, respectively, and the stack number $n = 4$. The material with intrinsic in-plane anisotropy serving as the soft core could be chosen as NiFeCo alloy. The saturation magnetizations for both regions are assumed to be $M_s = 650$ emu cm$^{-3}$, and the Gilbert damping constant $\alpha = 0.08$.

3.1. Numerical solution of analytical results

We first evaluate the analytic results for a perpendicular nanopillar without nanocore (i.e. $\delta = 0$). Figure 2(a) shows the applied spin-torque magnitude $|a_J|$ and the required critical torque factor $|a_{Jc}|$ as a function of $\theta$ in the absence of nanocore, where $|a_J|$ is taken at an applied current density of $J = 1.0 \times 10^7$ A cm$^{-2}$, and the angle $\theta$ denotes the free layer magnetization orientation with respect to the perpendicular direction of the fixed layer. It can be seen that $|a_J|$ increases with $\theta$ monotonically from $0^\circ$ to $180^\circ$, which is dominated by the scalar function $g(\theta)$ in Slonczewski’s model \[1\]. In contrast, the $|a_{Jc}|$ curve shows a hyperbolic shape, which reaches its maximum value at $\theta = 0^\circ$ and $180^\circ$, and goes to zero at $\theta = 90^\circ$. It is noticed that for the switching from parallel to antiparallel, the resistant effect of $|a_{Jc}|$ acts only when the magnetization rotates from $0^\circ$ to $90^\circ$ (i.e. the first stage). Once the magnetization passes the in-plane direction, the main contribution of the large perpendicular anisotropy field $H_{k1}$ in $|a_{Jc}|$ in turn helps the further rotation from $90^\circ$ to $180^\circ$. So the current-induced spin torque should overcome the barrier of $|a_{Jc}|$ at the initial magnetization direction of $\theta_m = 0^\circ$ for complete P $\rightarrow$ AP switching, since the $|a_{Jc}|$ has a maximum value at $\theta_m = 0^\circ$. Figure 2(b) shows the calculated magnitude difference between $|a_J|$ and $|a_{Jc}|$ for various current densities ($J$) during the first stage of P $\rightarrow$ AP switching ($\theta$ from $0^\circ$ to $90^\circ$). It can be seen that the value of $|a_J| - |a_{Jc}|$ can be larger or smaller than zero at $\theta = 0$ depending on how much current is applied. The critical current density for the sample without nanocore can be explicitly determined by setting $|a_J| - |a_{Jc}| = 0$ at $\theta_m = 0^\circ$ for the P $\rightarrow$ AP switching:

$$ J_c = -\frac{2eM_t\alpha}{\hbar g(\theta_c)} \left\{ H_{k1} \frac{M_z}{M_s} (1 - \delta) - 4\pi M_z + H_s \right\} - \frac{\alpha M_z}{2M_s} H_{k2}\delta \right\}. \quad (6) $$

Note that, for more generality of equation (6), we use here a critical angle $\theta_c$ instead of $\theta_m$ (for the P $\rightarrow$ AP switching, $\theta_c = \theta_m$). The numerically obtained critical current density $J_c$ from (6) is $-3.97 \times 10^7$ A cm$^{-2}$ according to the given parameters. For applied current above this critical point, e.g. $J = -4.70 \times 10^7$ A cm$^{-2}$ shown in figure 2(b), $|a_J| - |a_{Jc}|$ is always positive in the first switching stage for $\theta = 0 \rightarrow 90^\circ$, meaning that the spin torque generated by the current is enough to surpass the damping term. As a result, the magnetization will be turned to the in-plane direction, followed by the second stage switching process driven by the anisotropy field and spin torque; a complete P $\rightarrow$ AP switching can be achieved. If the applied current is lower than $J_c$,
Figure 2. (a) $|a_J|$ from equation (2) at $J = 1.0 \times 10^7$ A cm$^{-2}$ and $|a_{jc}|$ from equation (5) as a function of $\theta$, where $\theta$ is the angle between the magnetization directions of the pinned layer and the free layer. (b) The magnitude of $|a_J| - |a_{jc}|$ dependence on $\theta$ after applying various current densities during the P $\rightarrow$ AP switching for the $\delta = 0$ case. The critical current density is $J = -3.97 \times 10^7$ A cm$^{-2}$. (c) The corresponding micromagnetic-simulated switching curves at $J = -3.3 \times 10^7$ and $-4.7 \times 10^7$ A cm$^{-2}$.

... for example, $J = -3.3 \times 10^7$ A cm$^{-2}$, no switching occurs. This analytical solution is consistent with the micromagnetic simulation results, as shown in figure 2(c); the free-layer magnetization maintains the P alignment for $J = -3.30 \times 10^7$ A cm$^{-2}$, whereas a complete magnetization reversal from P to AP alignment occurs when $J$ is increased to $-4.70 \times 10^7$ A cm$^{-2}$.

For samples with a composite free layer containing a soft nanocore, their initial magnetization directions will slightly deviate away from the perpendicular direction, and the averaged z-component of magnetization ($M_z/M_z$) is no longer +1 or −1 in the remanence state. In this case, the magnetization switching will not start from $\theta_m = 0^\circ$ (P $\rightarrow$ AP) or $180^\circ$ (AP $\rightarrow$ P), but from a specific value of $\theta_m$ depending on the size of the nanocore. Accordingly, for the GMR pillar containing a soft nanocore, the critical switching current density $J_{sc}^{P\rightarrow AP}$ can be obtained from equation (6) at the corresponding $\theta_m$. For example, the average remanent $M_z$ of the free layer for $\delta = 12.5\%$ is $M_z/M_z = 0.89$, which corresponds to the initial state of the magnetization at $\theta_m = 27^\circ$. Figure 3(a) shows the dependence of $|a_J| - |a_{jc}|$ on the free layer magnetization direction denoted by angle $\theta$ for the $\delta = 12.5\%$ case. Note that the $J_{sc}^{P\rightarrow AP}$ is reduced to $-2.91 \times 10^7$ A cm$^{-2}$, which is much lower than the $J_{sc}^{P\rightarrow AP}$ of $-3.97 \times 10^7$ A cm$^{-2}$ for the $\delta = 0$ case, suggesting that the soft nanocore has a strong effect on $J_{sc}$ reduction.

For the AP $\rightarrow$ P switching, both $|a_J|$ and $|a_{jc}|$ reduce with $\theta$ decreasing from $180^\circ$ to $90^\circ$, as shown in figure 2(a). However, the corresponding curve of $|a_J| - |a_{jc}|$ versus $\theta$ exhibits

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nonmonotonic behavior with a minimum saddle point at $\theta = 148^\circ$ for $\delta = 12.5\%$, as shown in figure 3(b). This behavior is quite different from that of the P $\rightarrow$ AP switching in which $|a_j| - |a_{JC}|$ shows a monotonic rise with $\theta$ increasing (see figure 3(a)). It is noted that in the first stage of the AP–P switching (i.e. $\theta$ from 180$^\circ$ to 90$^\circ$), both $|a_j|$ and $|a_{JC}|$ decrease, as shown in figure 2(a), but the decreasing rate of $|a_j|$ is larger than that of $|a_{JC}|$ from $\theta = 180^\circ$ to 148$^\circ$ and subsequently becomes smaller from $\theta = 148^\circ$ to 90$^\circ$. As a result, a minimum value (saddle point) in the difference of $|a_j| - |a_{JC}|$ is formed at $\theta_{min} \sim 148^\circ$, as shown in figure 3(b).

For the AP $\rightarrow$ P switching, the calculated remanence state of the free layer in the absence of current is at $\theta_{in} = 153^\circ$, but successful switching always requires $|a_j| - |a_{JC}|$ to be positive. Thus the critical current density for the AP $\rightarrow$ P switching should be determined by $|a_j| - |a_{JC}| = 0$ at the minimum saddle point of $\theta_c = \theta_{min} = 148^\circ$, not at $\theta_{in} = 153^\circ$. In this way, we get $J_{c_{AP\rightarrow P}} = 0.88 \times 10^7$ A cm$^{-2}$. It is worth noting that such a slight change, in theory, can also be revealed by the micromagnetic simulation, as shown in figure 1, in which a small jump is observed at $J \approx 0.6 \times 10^7$ A cm$^{-2}$ for $\delta = 12.5\%$.

By summarizing the above analyses, we can conclude that the critical angle $\theta_c$, which is related to the switching current shown by equation (6), is dominated by the remanent state of magnetization of the composite free layer for the P $\rightarrow$ AP switching (i.e. $\theta_c = \theta_{in}$), and by the saddle point of the $|a_j| - |a_{JC}|$ for the AP $\rightarrow$ P switching (i.e. $\theta_c = \theta_{min}$). Figure 4(a) shows the critical angle $\theta_c$ dependence on the nanocore area ratio $\delta$. Note that, with the increase of $\delta$, the $\theta_c$ dramatically increases for the P $\rightarrow$ AP switching but varies little for the AP $\rightarrow$ P switching. Such changing behavior of $\theta_c$ can be seen more clearly in figure 4(b), which displays the curves of $|a_j| - |a_{JC}|$ versus $\theta$ for three kinds of nanocore ratios at their respective critical switching current. From the critical angle $\theta_c$, the analytical values of the critical switching
current can be immediately deduced from equation (6), which are summarized in figure 5 (open squares). It can be seen that $J_{c}^{P\rightarrow AP}$ decreases much more than $J_{c}^{AP\rightarrow P}$ after inserting a nanocore with a certain area ratio. $J_{c}^{P\rightarrow AP}$ drops from $-3.97 \times 10^{7}$ to $-2.91 \times 10^{7}$ A cm$^{-2}$, whereas $J_{c}^{AP\rightarrow P}$ reduces dramatically from $1.02 \times 10^{7}$ to $0.88 \times 10^{7}$ A cm$^{-2}$ with a nanocore of $\delta = 12.5\%$. We consider that the asymmetric change of $\theta_{c}$ as a function of $\delta$ discussed above is responsible for such an asymmetric $J_{c}$ reduction.

3.2. Micromagnetic simulations and the modified analytical model

In order to verify the analytical model, micromagnetic simulations were performed by using a finite-difference code based on the LLG equation including Slonczewski’s spin-torque term, which has been used in our previous studies [5, 17]. We assume that the free layer is 3 nm thick and $120 \times 80$ nm$^{2}$ in lateral dimension. The free layer is discretized into a two-dimensional array of mesh cells with each mesh cell dimension being $5 \times 5$ nm$^{2}$. In the simulation, besides the parameter values mentioned in the beginning of section 2, the exchange constant $A$ of the hard or soft region is set as $1.0 \times 10^{-6}$ erg cm$^{-1}$, whereas the coupling energy ($J_{ex}$) between the two regions is assumed to be $2.0$ erg cm$^{-2}$. The current-generated magnetic field and the current-self-heating effect are ignored. The simulated critical switching current as a function of the nanocore ratio is also given in figure 5. The simulation data show a similar trend of $J_{c}$ reduction but with even larger reduction magnitude than the analytical results for the same $\delta$. This quantitative discrepancy between the analytical and simulation results implies that the analytical model is still too ideal to describe the full mechanism of the switching process observed by micromagnetic simulations.

In the simple model described in section 2, the magnetic moments of the composite free layer were assumed to rotate coherently. However, inevitable incoherent switching among the hard and soft regions mediated by the domain nucleation and expansion process was clearly observed in the simulation [17]. During the switching process, the nanocore first rotates to...
the in-plane direction and then exerts a driving ‘force’ to affect the hard region through the exchange interaction. The hard region and the soft core are treated as two separate domains; we assume that the exchange interaction between the two regions could be rewritten as an additional Heisenberg type of exchange field ($H_{ex}$):

$$H_{ex} = J_{ex} \cdot S \cdot \cos(\theta_1 - \theta_2) / M_s \cdot V_1,$$

(7)

where $J_{ex}$ is the exchange constant in units of erg cm$^{-2}$, $S$ is the interfacial area between the hard and soft regions, and $\theta_1$ and $\theta_2$ are the corresponding magnetization directions of the two regions. $\theta_1$ is set as zero by assuming the magnetization of the hard region strictly along the perpendicular direction, and $\theta_2$ is taken from micromagnetic results for a given nanocore area ratio of $\delta$ [17]. Thus, $\cos(\theta_1 - \theta_2)$ is 0.78, 0.47, 0.24 and 0.14 for the $P \rightarrow AP$ switching and 0.52, 0.15, 0.0 and 0.0 for the opposite switching at $\delta = 4.2, 6.3, 9.4$ and 12.5%, respectively.

By inserting the exchange field $H_{ex}$ as an additional term of the effective field, the switching current density of equation (6) could be rewritten as

$$J_c = -\frac{2eM_z\alpha}{\hbar g(\theta_c)} \left\{ H_k \frac{M_z}{M_s} (1 - \delta) - 4\pi M_z + H_s \pm H_{ex} \right\} - \frac{\alpha M_z}{2M_s} H_{ex} \delta,$$

(8)

where the prefix sign ($\pm$) of $H_{ex}$ is determined by the switching direction. For the $P \rightarrow AP$ switching, with initial $M_z > 0$, the sign is taken to be negative, whereas for the $AP \rightarrow P$ switching, initial $M_z < 0$, the sign is positive. The numerical solution of the modified analytical model governed by equation (8) is also plotted in figure 5 (see the solid square symbols). Note that the reduction magnitude for both switching directions has been enhanced when $\delta$ is relatively small, and the $J_c$ values are quite close to the simulation results for $\delta = 4.2\%$. 

Figure 5. (a) Analytical and micromagnetic simulation results of the critical switching current versus the nanocore area ratio $\delta$ for both $P \rightarrow AP$ and $AP \rightarrow P$ switching. $J_c^{P\rightarrow AP}$ and $J_c^{AP\rightarrow P}$ have different reduction ratios and $J_c$ asymmetry is partially compensated due to the insertion of the nanocore.
However, for the higher $\delta$ case, the discrepancy is still very large. This is because the coupling strength decreases with an increase in the soft core size; the locally coupled magnetic moments could not be maintained in the same direction; they change gradually from the hard region (prefer to stay in the out-of-plane direction) to the soft region (prefer to be the in-plane direction). Thus, the average values of $\theta_1$ and $\theta_2$ in this model are no longer appropriate to represent such gradual variations, resulting in the discrepancy in $J_c$ between the analytical and simulation curves when the GMR pillar contains a big nanocore.

4. Conclusions

In summary, an analytical model is presented to deduce the switching current behavior in perpendicularly magnetized GMR nanopillars with a nanocore inside the free layer. Combining the simulations with the analytical results, most of the physical origins including the asymmetric critical switching current, current reduction by inserting the soft nanocore and the improvement of switching symmetry could be interpreted well. Firstly, the asymmetric switching current $(J^\text{P}\rightarrow\text{AP}_c > J^\text{AP}\rightarrow\text{P}_c)$ observed in the perpendicular metallic nanopillars originates from the intrinsic difference in the spin transfer torque efficiency between the negative and positive current directions. Moreover, the stray dipole field $H_s$ in equation (6) produced by the fixed layer also provides some contributions to the asymmetry switching. Secondly, by inserting the soft nanocore into the free layer, the observed difference in $J_c$ reduction between the $\text{P}\rightarrow\text{AP}$ and $\text{AP}\rightarrow\text{P}$ switching could be attributed to the current flowing direction dependence of the switching behavior. That is, for the $\text{P}\rightarrow\text{AP}$ switching, the critical current is determined by the initial magnetization direction according to the analytical model, whereas for the $\text{AP}\rightarrow\text{P}$ switching, the critical current is determined by the minimum saddle point in the $|a_J| - |a_{Jc}|$ curve, which is less sensitive to the nanocore ratio. It is important that this asymmetric reduction in $J_c$ could partially compensate for the asymmetric switching current, leading to the switching symmetry getting improved to a certain extent. Thirdly, it is interesting that a very slight jump observed in the antiparallel to parallel switching curve by the micromagnetic simulation could also be explained by this analytical model.

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References

[1] Slonczewski J C 1996 J. Magn. Magn. Mater. 159 L1–7
[2] Berger L 1996 Phys. Rev. B 54 9353–8
[3] Katine J A, Albert F J, Buhrman R A, Myers E B and Ralph D C 2000 Phys. Rev. Lett. 84 3149–52
[4] Jiang Y, Nozaki T, Abe S, Ochiai T, Hirohata A, Tezuka N and Inomata K 2004 Nat. Mater. 3 361–4
[5] Liu Y, Zhang Z, Freitas P P and Matins J L 2003 Appl. Phys. Lett. 82 2871–3
[6] Yagami K, Tulapurkar A A, Fukushima A and Suzuki Y 2004 Appl. Phys. Lett. 85 5634–6
[7] Fuchs G D, Krivorotov I N, Braganca P M, Emley N C, Garcia A G F, Ralph D C and Buhrman R A 2005 Appl. Phys. Lett. 86 152509
[8] Diao Z et al 2007 Appl. Phys. Lett. 90 132508
[9] Meng H and Wang J P 2006 Appl. Phys. Lett. 89 152509
[10] Zhang Y, Zhang Z, Liu Y, Ma B and Jin Q Y 2007 Appl. Phys. Lett. 90 112504
[11] Mangin S, Ravelosona D, Katine J A, Carey M J, Terris B D and Fullerton E E 2006 Nat. Mater. 5 210–5
[12] Ravelosona D, Mangin S, Lemaho Y, Katine J A, Terris B D and Fullerton E E 2006 Phys. Rev. Lett. 96 186604
[13] Seki T, Mitani S, Yakushiji K and Takanashi K 2006 Appl. Phys. Lett. 88 172504
[14] Meng H and Wang J P 2006 Appl. Phys. Lett. 88 172506
[15] Nakayama M, Kai T, Shimomura N, Amano M, Kitagawa E, Nagase T, Yoshikawa M, Kishi T, Ikegawa S and Yoda H 2008 J. Appl. Phys. 103 07A710
[16] Meng H and Wang J P 2007 IEEE Trans. Magn. 43 2833–5
[17] Li X, Zhang Z, Jin Q Y and Liu Y 2008 Appl. Phys. Lett. 92 122502
[18] Yao X F, Meng H, Zhang Y S and Wang J P 2008 J. Appl. Phys. 103 07A717
[19] Kovalev A A, Bauer G E W and Brataas A 2006 Phys. Rev. B 73 054407
[20] Slonczewski J C 2005 Phys. Rev. B 71 024411
[21] Kovalev A A, Brataas A and Bauer G E W 2002 Phys. Rev. B 66 224424
[22] Xiao J, Zangwill A and Stiles M D 2004 Phys. Rev. B 70 172405
[23] Chang J H and Chang C R 2008 Intermag 2008 Conf. (Madrid, Spain, 2008) No. DP-07
[24] Lee K J, Redon O and Dieny B 2005 Appl. Phys. Lett. 86 022505

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