Fast Track Communication

Ultra-low-energy computing paradigm using giant spin Hall devices

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Abstract
The spin Hall effect converts charge current to spin current, which can exert spin-torque to switch the magnetization of a nanomagnet. Recently, it has been shown that the ratio of spin current to charge current using the spin Hall effect can be made greater than unity by using the areal geometry judiciously, unlike the case of conventional spin-transfer-torque switching of nanomagnets. This can enable an energy-efficient means to write a bit of information in nanomagnets. Here, we study the energy dissipation in such spin Hall devices. By solving the stochastic Landau–Lifshitz–Gilbert equation of magnetization dynamics in the presence of room-temperature thermal fluctuations, we show a methodology to simultaneously reduce the switching delay, its variance and energy dissipation, while lateral dimensions of the spin Hall devices are scaled down.

Keywords: spin Hall effect, nanomagnets, ultra-low-energy computing, magnetization dynamics

1. Introduction
Spintronics is a promising field of research that can possibly replace the traditional charge-based electronics [1–3]. Spin-transfer torque (STT) is a current-induced magnetization switching (CIMS) mechanism in which the magnetization of a nanomagnet can be switched between its two stable states [4–7] or it may lead to an oscillatory motion of the magnetization [8]; however, the energy dissipation in such a switching mechanism is too high for practical application purposes compared with the traditional charge-based electronics [9]. There are other mechanisms that are coming along for energy-efficient switching of a bit of information, e.g. electric-field-induced magnetization switching in multiferroic heterostructures [10–14], perpendicular anisotropy [15–17] and coupled polarization–magnetization switching in single-phase multiferroic materials [18–21]. However, one mechanism that has recently received attention is the utilization of the spin Hall effect, which was first recognized by D’yakonov and Perel’ [22], following which there have been both theoretical studies [23–26] and experimental investigations in semiconductors [27–30]. Utilizing the spin Hall effect to generate a sufficient spin current for technological purposes of exciting magnetization dynamics was severely limited [31]; however, there have been recent resurgence of interest [31–34] due to the giant spin Hall effect of exerting spin-torque, which can be used to switch the magnetization direction of a nanomagnet using different spin Hall materials, e.g. platinum [35–38], tantalum [39], tungsten [40] and CuBi [41].

Figure 1 shows a schematic diagram of a spin Hall device. A charge current flows laterally in the spin Hall material layer and a perpendicular spin current is generated through the cross-section of the structure, which can exert spin-torque on the free layer nanomagnet and switch its magnetization. In conventional STT devices, the charge...
current gets spin-polarized through a fixed layer. However, passing high current during the switching of magnetization occasionally damages the thin insulator layer [39]. Hence, the giant spin Hall devices offer a great advantage over the traditional STT devices. Note that the read current, which is small, still needs to be passed perpendicular to the cross-section of the spin Hall devices and hence the fixed layer in a magnetic tunnel junction (MTJ) structure is required to detect the magnetization states of the free layer by passing a small charge current. Since the charge current flows laterally through the spin Hall material layer accumulating spins of opposite polarities on its opposite surfaces, which generates a spin current (of current density \( J_s \)) in the \( x \)-direction with spin polarization in the \( z \)-direction. For the direction of charge current and spin current shown in the diagram, the direction of spin polarization at the free layer–spin Hall material layer interface will be in the \( +z \)-direction for materials with positive spin Hall angle (e.g. Pt), while it will be in the \( -z \)-direction for materials with negative spin Hall angle (e.g. CuBi). Since the two mutually anti-parallel stable magnetization orientations of the free layer along the \( z \)-axis encode the logic bits 0 and 1, the spin-torque acting in the free layer needs to switch the magnetization in either direction and it can be performed by changing the direction of the charge current. Note that unlike the case of traditional STT devices, the charge current is not spin-polarized by the fixed layer; however, the fixed layer and the insulator (e.g. MgO) are required to read the magnetization state of the free layer by passing a small charge current in the \( x \)-direction via the tunnelling magnetoresistance (TMR) mechanism. In a standard spherical coordinate system, \( \theta \) is the polar angle and \( \phi \) is the azimuthal angle.

2. Model

We consider a free layer nanomagnet in the shape of an elliptical cylinder with its elliptical cross-section lying on the \( y-z \) plane; the major axis is along the \( z \)-direction and the minor axis is along the \( y \)-direction (see figure 1). The dimensions along the \( z \)-, \( y \)- and \( x \)-directions are \( a, b \) and \( l \) \((a > b \gg l)\), respectively. So the lateral area of the spin Hall device is \( A = (\pi/4)ab \) and the nanomagnet’s volume is \( V = (\pi/4)ab^2l \).

In a standard spherical coordinate system, \( \theta \) is the polar angle and \( \phi \) is the azimuthal angle. Due to shape anisotropy, the two degenerate magnetization states along the \( z \)-direction \((\theta = 0^\circ \text{ and } 180^\circ)\) can store a binary bit of information. The \( y \)-axis is the in-plane hard axis and \( x \)-axis is the out-of-plane hard axis. We can write the shape anisotropy energy of the nanomagnet as follows:

\[
E_{\text{shape}}(\theta, \phi) = \frac{1}{2} M [H_k + H_d \cos^2 \phi] \Omega \sin^2 \theta, \tag{1}
\]

where \( M = \mu_0 M_s \), \( \mu_0 \) is the permeability of free space, \( M_s \) is the saturation magnetization, \( H_k = (N_{dy} - N_{dz}) M_s \) is the Stoner–Wohlfarth switching field [46], \( H_d = (N_{dx} - N_{dz}) M_s \) is the out-of-plane demagnetization field [46], and \( N_{dm} \) is the energy barrier between the two stable magnetization states can be expressed from equation (1) (by putting \( \phi = \pm 90^\circ \)) as

\[
E_{\text{barrier}} = \frac{1}{2} M H_k \Omega. \tag{2}
\]

The magnetization \( M \) of the nanomagnet has a constant magnitude but a variable direction, and hence we can represent it by a vector of unit norm \( n_m = M/|M| = \hat{e}_r \), where \( \hat{e}_r \) is the unit vector in the radial direction in the spherical coordinate system represented by \((r, \theta, \phi)\); the other two unit vectors in the spherical coordinate system are \( \hat{e}_\theta \) and \( \hat{e}_\phi \) for \( \theta \) and \( \phi \) rotations, respectively.

The effective field and torque acting on the magnetization due to the gradient of potential landscape can be expressed as

\[
H_{\text{eff}}(\theta, \phi) = -\nabla E_{\text{shape}}(\theta, \phi) = -(\partial E_{\text{shape}}/\partial \theta) \hat{e}_\theta -
\]
its magnitude is equal to $2T$.

$T_k(\theta, \phi) = -B_{\text{shape}}(\phi) \sin(2\theta) \hat{e}_\phi - B_{\text{shape, } \phi}(\phi) \sin \theta \hat{e}_\theta,$

(3)

where

\begin{align*}
B_{\text{shape}}(\phi) &= \frac{1}{2} M [H_k + H_d \cos^2 \phi] \Omega, \\
B_{\text{shape, } \phi}(\phi) &= \frac{1}{2} M H_d \Omega \sin(2\phi).
\end{align*}

 Passage of a spin current $I_s$ in the $x$-direction with spin polarization along the $z$-direction generates an STT that is given by [4]

$$T_{\text{STT}}(t) = -s \mathbf{n}_m(t) \times \mathbf{n}_s \times \mathbf{n}_m(t) = s \sin \theta \hat{e}_\theta,$$

(6)

where $s = (h/2e)I_s$ is the spin angular momentum deposition per unit time, the unit vector $\mathbf{n}_s = \hat{e}_s$ is in the direction of spin polarization since we want to rotate the magnetization from the $-z$-axis to the $+z$-axis, and we have used the identity $\hat{e}_s = \cos \theta \hat{e}_\theta - \sin \theta \hat{e}_\phi$. No asymmetry in STT switching or field-like torque is considered here [48, 49, 56].

The random thermal fluctuations are incorporated via a random thermal field in Cartesian coordinates. We assume the random thermal field with zero mean does not cause any net energy dissipation, while the energy dissipated in the nanomagnet due to Gilbert damping can be expressed as $E_{\text{damp}} = \int_0^\tau P_{\text{damp}}(t) \, \text{d}t$, where $\tau$ is the switching delay and $P_{\text{damp}}(t)$ is the power dissipated at time $t$ given by

$$P_{\text{damp}}(t) = \frac{\alpha \gamma}{(1 + \alpha^2) M \Omega} |T_k(\theta(t), \phi(t)) + T_{\text{STT}}(t)|^2.$$  

(13)

The thermal field with zero mean does not cause any net energy dissipation but it causes variability in the energy dissipation by scuttling the trajectory of magnetization.

If the magnetization situates exactly along the easy axis, i.e. $\sin \theta = 0 (\theta = 0^\circ \text{ or } \theta = 180^\circ)$, the torque acting on the magnetization given by equations (3) and (6) becomes zero. That is why only thermal fluctuations can deflect the magnetization vector exactly from the easy axis. The magnetization fluctuates around an easy axis due to thermal agitations and hence we get a distribution of the initial angles ($\theta_{\text{initial}}, \phi_{\text{initial}}$). We consider this initial distribution when the magnetization starts switching from $\theta \approx 180^\circ$. We perform a moderately large number (10 000) of simulations in the presence of thermal fluctuations and when the final value $\theta_{\text{final}}$ becomes $\leq 4.5^\circ$ (note that the mean value of $\theta_{\text{initial}}$ is $\approx 4.5^\circ$), the switching is deemed to have completed. Then, the mean and standard deviation of the switching delay distribution ($\tau_{\text{mean}}$ and $\tau_{\text{std}}$, respectively), and the mean of energy dissipation $E_{\text{damp, mean}}$ are extracted from the simulations. (See figure 2 and table 1 later.)

The energy dissipation due to Gilbert damping is of the order of the energy barrier height; however, the major part of the energy dissipation occurs due to Ohmic loss in the spin Hall material since the charge current $I_c$ flows through it in the $y$-direction (see figure 1). The spin current $I_s$ flows in the $x$-direction, and the ratio of the spin-to-charge current can be expressed as

$$\frac{I_s}{I_c} = \frac{J_s}{\bar{J}_c} A_c = \frac{b}{I_{\text{SH}}},$$

(14)

where $J_s$ ($J_c$) is the spin (charge) current density, $A_c$ ($A_s$) is the area through which the spin (charge) current flows, $\Theta_{\text{SH}}$ is the spin Hall angle of the spin Hall material used, and $I_{\text{SH}}$ is the thickness of the spin Hall material layer. The geometric factor $b/I_{\text{SH}}$ can be selected much greater than one and, hence, having $\Theta_{\text{SH}} b > I_{\text{SH}}$ can make $I_s > I_c$.

The power dissipation in the spin Hall material can be expressed as

$$P_d = I_s^2 R = \left( \frac{I_{\text{SH}} I_s}{\Theta_{\text{SH}} b} \right)^2 \left( \frac{2}{\rho \pi a I_{\text{SH}}} \right) = \frac{1}{2} \left( \frac{\rho}{\Theta_{\text{SH}}^2} \right) I_{\text{SH}}^2 I_s^2,$$

(15)
where $\rho$ is the resistivity of the spin Hall material and $R$ is the resistance of the spin Hall material layer. The energy dissipation in the spin Hall material layer can be expressed as

$$E_d = P_d T_p = \frac{1}{2} \left( \frac{\rho}{\rho_{SH}} \right) \left( I_{SH} \right)^2 A, \quad (16)$$

where $T_p$ is the time period until which the charge current is kept active.

3. Results

For the free layer nanomagnet, we consider the widely used material CoFeB, which has a low saturation magnetization $M_s = 8 \times 10^5 \text{ A m}^{-1}$ [50] and a low Gilbert damping parameter $\alpha = 0.01$. Note that the damping parameter can be modified depending on the adjacent spin Hall material layer due to spin pumping [51]. We choose CuBi as the spin Hall material since it has the lowest $\rho/\rho_{SH}$ factor ($\rho = 10 \mu\Omega\text{cm}, \rho_{SH} = -0.24$ measured at 10 K [41]) among the other materials utilized in current experiments with an eye to reduce the energy dissipation (see equation (16)). We can also possibly utilize platinum as the spin Hall material layer that has $\rho \sim 15 \mu\Omega\text{cm}$ [36]. $\rho_{SH} = 0.07$ [38] measured at room temperature; however, it will incur an energy dissipation of one order more than that of CuBi. Note that platinum increases magnetization damping (i.e., increases the minimum switching current) of CoFeB considerably and the damping parameter is about three times compared to when tantalum is used [39].

Note that CoFeB has a resistivity of $100 \mu\Omega\text{cm}$ [52], which is 10 times more than that of a CuBi spin Hall material layer. Hence the current shunting effect [53, 54] through the CoFeB layer is ignored. Therefore, the purpose of using a low-resistive spin Hall material layer is also to tackle the issue of the current shunting effect, apart from reducing the energy dissipation. We do need to consider the current shunting effect while utilizing tantalum or tungsten as the spin Hall material layer since they have the resistivity of the same order as of CoFeB [39, 40]. We consider here in-plane switching of magnetization; however, perpendicular switching of magnetization has been demonstrated [16, 39, 55, 56] and can also be considered, particularly to scale down the lateral area of the devices further.

We use both thicknesses $t_{SH}$ and $l$ as 2 nm. We vary the lateral dimensions $a$ and $b$ of the nanomagnet for different cases considered and we choose the dimensions of the nanomagnet so that it has a single ferromagnetic domain [47, 57]. We always keep the energy barrier $E_{\text{barrier}} = 0.8 \text{eV}$ or $32 \text{kT}$ at room temperature ($T = 300 \text{K}$). Following the Boltzmann distribution, this means that the error probability due to spontaneous reversal of magnetization is $e^{-E_{\text{barrier}}/kT} = e^{-32}$ or $10^{-14}$, which is low enough for application purposes.

We can choose a higher barrier height leading to even lower error probability depending on the application requirements. We will now go through the following three cases.

Case (a). We consider a nanomagnet with dimensions $a = 150 \text{nm}, b = 100 \text{nm}$ and $l = 2 \text{nm}$. We solve the stochastic LLG equation for 10000 times and find that it requires about $I_s = 1.6 \text{mA}$ to switch always successfully, while the switching current is kept active for 2.5 ns. The corresponding charge current is $I_c = 133.3 \mu\text{A}$. The demagnetization factor $(N_{dx}, N_{dy}, N_{dz}) = (0.9468, 0.0339, 0.019)$ [47], $H_{k} = 0.0148 \text{T}$ and $H_{z} = 0.9177 \text{T}$. The switching delay distribution is plotted in figure 2(a). The mean of the switching delay and its standard deviation are 1.03 ns and 0.21 ns, respectively. The distributions look like log-normal distributions and can be fitted accordingly. The means and the standard deviations are directly calculated from the numerically computed distributions.

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Case (b). We now reduce the lateral dimensions of the nanomagnet and choose the lateral dimensions to be $a = 100 \text{nm}, b = 30 \text{nm}$ with an eye to increase the device density on a chip. The thickness $l$ is kept the same as for case (a). Hence, both the lateral area and the volume decrease by a factor of 5. Note that the energy barrier between the two stable states increases due to the modification of the magnetic anisotropies $H_k[47, 57]$. We always keep $H_k$, $H_{z}$ and $H_{z}$ constant (see equation (2)) at this reduced volume by choosing the elliptical cross-section more anisotropic. The demagnetization factor $(N_{dx}, N_{dy}, N_{dz}) = (0.8829, 0.0953, 0.0218)$ [47], $H_{k} = 0.0739 \text{T}$ and $H_{z} = 0.7917 \text{T}$. The anisotropic field $H_k$ increases due to the modification of the demagnetization factors at the chosen dimensions [47]. However, at a reduced volume, the magnetization becomes more prone to thermal fluctuations (see equation (7)). But the
STT switching current also mitigates the detrimental effects of thermal agitations. Since in this case the current needs to switch a nanomagnet of a smaller volume (see equations (11) and (12)), we show that it is possible to adjust the switching current such that overall we can achieve a better performance metrics for both switching delay and energy dissipation at this reduced volume.

According to equation (15), we scale down $I_s$ by a factor of $\sqrt{5}$ to keep the power dissipation constant. The corresponding distribution of the switching delay is shown in figure 2(b). Note that both the mean and the standard deviation of the switching delay have got reduced by half compared with case (a). The switching current is kept on until 1.2 ns and hence the energy dissipation is reduced by more than half compared with case (a). Note that even if the spin current $I_s$ is reduced, the charge current required in this case has increased compared with case (a) due to the decrease in the minor axis $b$ of the elliptical cross-section of the nanomagnet (see equation (14)). Next, we consider another case where the spin current $I_s$ is reduced further to keep the charge current the same compared with case (a).

**Case (c).** We choose the same dimensions of the nanomagnet as in case (b) and the same charge current as in case (a) (see table 1). The demagnetization factor, $H_k$, and $H_d$ are the same as in the previous case. The corresponding switching delay distribution is plotted in figure 2(c). Note that both the mean and the standard deviation of the switching delay distribution have increased compared with case (b) due to the decrease in $I_s$; however, the metrics is still much better than that of case (a) (see table 1). The energy dissipation $E_d$ has reduced by more than half, compared with case (b), to 204 aJ, which is due to the decrease in the spin current $I_s$.

It should be noted that it is not only the mean of the switching delay distribution, but also the standard deviation in switching delay that plays an important role in setting the clock period of magnetization switching for application purposes. A higher standard deviation would lead to setting a higher clock period. In this paper, it is shown that both the mean and the standard deviation of the switching delay can be reduced simultaneously, while the lateral area of the giant spin Hall devices is scaled down.

### 4. Discussions

From equation (14), it should be noted that the spin diffusion length $\lambda_{SH}$ of the spin Hall material is not considered in the expression. For a thick spin Hall material layer ($t_{SH} \gg \lambda_{SH}$), there is no need to consider $\lambda_{SH}$. However, we should choose the thickness of the spin Hall material layer $t_{SH}$ small since the charge current (for a required spin current) decreases with the decrease in $t_{SH}$. It is possible to add a spin-sink layer at the bottom of a thin spin Hall material layer (see figure 1) to avoid any backflow of spins. For example, see [58] for some experimental results; however, research on such a subject is quite emerging. For CuBi utilized as a spin Hall material layer, such experimental data are not available; however, this concept of adding a spin-sink layer is quite general. Also it should be noted that there is controversy on the experimentally measured spin diffusion length for spin Hall materials [58]. Since for all the three cases in table 1, the results correspond to the same thickness of the spin Hall material layer, the comparative nature of the analysis is not quite affected. The analysis presented here depicts the necessity of decreasing the thickness of the spin Hall material layer to decrease the charge current and consequently to reduce the energy dissipation.

It is imperative to compare the energy savings utilizing the giant spin Hall effect compared with the traditional way of exerting spin-torque. The energy savings accrue from the decrease in the charge current due to the geometric factor and the decrease in the resistance of the charge flow path compared with the MTJ stack. The reduction in energy dissipation is as high as 3–4 orders of magnitude compared with the conventional STT switching mechanism [59, 60] and domain-wall racetrack memory [61, 62].

Although the energy dissipation in these giant spin Hall devices has got reduced to the order of 0.1 fJ, it can be further reduced by having a spin Hall material that has an even lower $\rho/\delta_{SH}$ factor (see equation (16)), i.e. having a material with a lower resistivity and a higher spin Hall angle. The target would be the reduction in energy dissipation by a factor of 2 more to be competitive with other emerging technologies [10]. The switching delay and area of a device also need to be competitive with the traditional transistor based technology [63]. The non-volatility of nanomagnets in these giant spin Hall devices can be utilized to devise a possibly better architecture in terms of performance metrics for application purposes.

### 5. Conclusions

In conclusion, we have analysed the energy dissipation in recently proposed spin Hall devices exploiting the giant spin Hall effect. After formulating the energy dissipation, we solved the stochastic Landau–Lifshitz–Gilbert equation of magnetization dynamics in the presence of room-temperature thermal fluctuations to present a methodology in which both the energy dissipation and switching delay (and its variance)
can be reduced simultaneously, while the lateral dimensions of the spin Hall devices are scaled down. The energy dissipation turns out to be of several orders of magnitude less than that of the traditional spin-transfer-torque devices. This field is still emerging and with suitable spin Hall materials, the energy dissipation can be reduced further. This opens up an energy-efficient avenue to control a bit of information in nanomagnetic memory and logic systems for our future information processing paradigm.

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