Fast Track Communication

Electric field-induced magnetization switching in interface-coupled multiferroic heterostructures: a highly-dense, non-volatile, and ultra-low-energy computing paradigm

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Abstract
Electric field-induced magnetization switching in multiferroic magnetoelectric devices is promising for computing purposes in beyond Moore’s law era. We show here that interface-coupled multiferroic heterostructures, i.e., a ferroelectric layer coupled with a ferromagnetic layer, are particularly suitable for highly-dense, non-volatile, and ultra-low-energy computing. By solving the stochastic Landau–Lifshitz–Gilbert equation of magnetization dynamics in the presence of room-temperature thermal fluctuations, we demonstrate that error-resilient switching of magnetization is possible with a sub-nanosecond delay while expending only a minuscule amount of energy, of \( \sim 1 \) attojoule. Such devices can be operated by drawing energy from the environment without the need for an external battery.

Keywords: multiferroics, nanomagnets, ultra-low-energy computing, magnetization dynamics

(Some figures may appear in colour only in the online journal)

\[ \text{Online supplementary data available from stacks.iop.org/JPhysD/47/252002/mmedia} \]

1. Introduction

The electric field-induced magnetization switching mechanism holds profound promise for computing in beyond Moore’s law era [1, 2]. In multiferroic magnetoelectrics, the application of an electric field can rotate the magnetization via the converse magnetoelectric effect; however, such materials in single-phase usually have issues of weak coupling between polarization and magnetization and they operate only at low temperatures [3, 4]. Although new concepts may come along regarding switching in single-phase materials [5, 6], strain-mediated multiferroic heterostructures [2, 3, 7, 8] consisting of a piezoelectric layer coupled to a magnetostrictive nanomagnet, is shown to be very effective. With appropriate choice of materials, when a voltage of a few millivolts is applied across such heterostructures, the piezoelectric layer gets strained and the strain is elastically transferred to the magnetostrictive layer, rotating its magnetization. Such a switching mechanism dissipates a minuscule amount of energy, of \( \sim 1 \) attojoule (aJ) with a sub-nanosecond switching delay at room-temperature [9]. This study has opened up a new field called straintronics [1, 10, 11] and experimental efforts to demonstrate electric field-induced
magnetization switching are emerging [12–15]. In a strain-mediated multiferroic heterostructure, the strain transferred by the piezoelectric layer to the magnetostrictive nanomagnet can only rotate the magnetization $90^\circ$ in a steady-state consideration [16]. Although there are proposals of $90^\circ$ switching mechanisms [12, 13, 17], it is explained that a complete $180^\circ$ switching is possible if we consider the dynamics of magnetization rather than assuming a steady-state scenario; basically, the magnetization’s excursion out of the magnet’s plane provides an equivalent asymmetry to cause switching in the correct direction [2, 16].

Although the aforesaid strain-mediated mechanism in multiferroic heterostructures is promising, it would be of substantial interest if there existed a strong coupling between the polarization and magnetization at the heterostructure interface. Recently, interface-coupled multiferroics are proposed based on density functional theory (DFT) of first-principles calculations [18]. Despite currently lacking experimental verification for this specific case, considering that first-principles calculations have been proved to be very useful [19] and with the experimental progress on a similar front [20–24] (also using ferromagnetic oxides [25, 26] rather than ferromagnetic metals), there is considerable interest in such a coupling mechanism [18, 27–31]. Figure 1 depicts the interface coupling between polarization and magnetization in a multiferroic heterostructure. The polarization direction in the P-layer determines the ground state of the trilayer $M_1$/spacermagnet $M_2$. For polarization $P_1$, parallel alignment ($P$-alignment) in the trilayer is preferred, while for the polarization $P_1$, anti-parallel alignment ($AP$-alignment) in the trilayer is preferred. This unique coupling phenomenon, along with electric field-induced polarization switching, makes the switching of magnetization in the $M_1$-layer non-volatile. Also, if a voltage with a certain polarity is applied and maintained, the state of the system remains unaltered. This is advantageous over the strain-mediated switching, which just toggles the magnetization states. There are other exchanged coupled systems with an insulating spacer layer, but the interface exchange coupling energy is small [32, 33]. Also, there are other schemes with a non-magnetic spacer layer to preserve large interlayer exchange coupling; however, the electric field required is high and also the switching is volatile [34].

Here, we study the magnetization dynamics in the interface-coupled multiferroic heterostructures by solving the stochastic Landau–Lifshitz–Gilbert (LLG) equation in the presence of room-temperature thermal fluctuations. Such a phenomenological study of switching has been very useful in understanding the performance metrics of magnetic devices [1, 2, 9]. First, we model the interfacial anisotropy in the interface-coupled multiferroic heterostructures and then we analyse the dynamics of magnetization, which shows that switching in sub-nanosecond delay is possible while expending only $\sim 1$ aJ of energy at room-temperature. The strong interface anisotropy makes the switching error-resilient and fast, and it allows us to work with nanomagnets with small dimensions, i.e., the magnetization is stable with $\sim 10$ nm lateral dimensions even in the presence of room-temperature thermal fluctuations. Such superior performance metrics of area, delay, and energy are particularly suitable for computing purposes in beyond Moore’s law era.

2. Model

Figure 1 shows the schematics of the interface-coupled multiferroic magnetoelastic devices (see [18]). The unique coupling between the polarization in the P-layer and the trilayer $M_1$/spacermagnet $M_2$ allows the polarization direction to dictate the magnetic ground state in the trilayer. If the polarization points downward ($P_1$), P-alignment in the trilayer is preferred while an upward polarization ($P_2$) prefers the AP-alignment. Application of a voltage with the correct polarity can switch the polarization and hence the magnetization $M_1$ gets switched too due to interface coupling. At the bottom of the figure, the axis assignment for the dynamical motion of magnetization $M_1$ in the standard spherical coordinate system is shown.

$$E_I(\theta, t) = -M H_I(t) \cos \theta,$$  

(1)
where \( M = \mu_0 M_s \) and \( M_s \) is the saturation magnetization, and \( H_I \) is the interfacial anisotropy field. If \( H_I = -H_{I_{\text{max}}} \), the ground state of magnetization \( M_1 \) points along \( \theta = 180^\circ \) and if we vary \( H_I \) from \(-H_{I_{\text{max}}} \) to \( H_{I_{\text{max}}} \), the ground state orients along \( \theta = 0^\circ \). The total anisotropy of the magnet is the sum of the interface anisotropy along with the other anisotropies like magnetocrystalline anisotropy and shape anisotropy [2, 9]; however, due to strong interfacial anisotropy compared to the other anisotropies, we consider only the interfacial anisotropy (i.e., \( E_{\text{total}} \simeq E_I \)) for brevity. We assume that the nanomagnet has the shape of an elliptical cylinder with the ellipse’s major axis along the \( z \)-direction, so that the magnetic easy axis is along the \( \pm z \)-direction.

The magnetization \( M \) of the single-domain nanomagnet \( M_1 \) (having constant magnitude of magnetization but a variable direction) can be represented by the unit vector in the radial direction \( \hat{e}_r \) in the spherical coordinate system \((r, \theta, \phi)\), i.e., \( n_m = M/|M| = \hat{e}_r \). 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 torque \( T_I \) acting on the magnetization due to interface anisotropy can be derived from the gradient of the energy and is given by

\[
T_I(\theta, t) = -n_m \times \nabla E_I(\theta, t) = -M H_I(\theta) \sin \theta \hat{e}_\phi. \tag{2}
\]

Note that the torque \( T_I \) acts along the out-of-plane direction, so that the magnetization can deflect out of the magnet’s plane (i.e., \( \phi \) can deflect from \( \pm 90^\circ \)).

The effect of random thermal fluctuations is incorporated via a random magnetic field \( h(t) = h_i(t) \hat{e}_x + h_y(t) \hat{e}_y + h_z(t) \hat{e}_z \), where \( h_i(t) (i = x, y, z) \) are the three components of the random thermal field in Cartesian coordinates. We assume the properties of the random field \( h(t) \) as described in [35]. The random thermal field can be written as [35]

\[
h_i(t) = \sqrt{\frac{2kT}{|y|M \Omega \Delta t}} G_{(0,1)}(t), \quad (i = x, y, z), \tag{3}
\]

where \( \alpha \) is the dimensionless phenomenological Gilbert damping parameter, \( \gamma \) is the gyromagnetic ratio for electrons, \( 1/\Delta t \) is the attempt frequency of thermal noise, \( \Omega \) is the volume, and the quantity \( G_{(0,1)}(t) \) is a Gaussian distribution with zero mean and unit variance.

The thermal field and the corresponding torque acting on the magnetization per unit volume can be written as \( H_{TH}(\theta, \phi, t) = P_\theta(\theta, \phi, t) \hat{e}_\theta + P_\phi(\theta, \phi, t) \hat{e}_\phi \) and \( T_{TH}(\theta, \phi, t) = n_m \times H_{TH}(\theta, \phi, t) \), respectively, where

\[
P_\theta(\theta, \phi, t) = M [h_i(t) \cos \theta \cos \phi + h_y(t) \cos \theta \sin \phi - h_z(t) \sin \theta], \tag{4}
\]

\[
P_\phi(\theta, \phi, t) = M [h_i(t) \cos \phi - h_y(t) \sin \phi]. \tag{5}
\]

The magnetization dynamics under the action of the torques \( T_I \) and \( T_{TH} \) is described by the stochastic LLG equation as follows.

\[
\frac{dn_m}{dt} = -\alpha \left( n_m \times \frac{dn_m}{dt} \right) = -\frac{|y|}{M} [T_I(t) + T_{TH}(t)]. \tag{6}
\]

Solving the above equation analytically, we get the following coupled equations of magnetization dynamics for \( \theta \) and \( \phi \):

\[
(1 + \alpha^2) \frac{d\theta}{dt} = \frac{|y|}{M} [-\alpha M H_I(t) \sin \theta + (\alpha P_\theta(\theta, \phi, t) + P_\phi(\theta, \phi, t))], \tag{7}
\]

\[
(1 + \alpha^2) \frac{d\phi}{dt} = \frac{|y|}{M} [M H_I(t) - |\sin \theta|]^{-1} \times (P_\theta(\theta, \phi, t) - \alpha P_\phi(\theta, \phi, t)) \quad (\sin \theta \neq 0). \tag{8}
\]

We solve the above two coupled equations numerically to track the trajectory of magnetization over time, in the presence of room-temperature thermal fluctuations.

From equations (7) and (8), we see that the torque acting in the \( \phi \) direction is much higher than the torque exerted in the \( \theta \) direction since the damping parameter \( \alpha \ll 1 \). Although the thickness of the nanomagnet is small (i.e., \( l \ll b < a \) and the demagnetization factors \( N_{Ax} \gg N_{Ay} > N_{Az} \), magnetization cannot remain on the magnet’s plane \((y-z \text{ plane, } \phi = \pm 90^\circ)\) since the interface coupling energy is a few orders of magnitude higher than the shape anisotropy energy. Thus, the magnetization keeps rotating in the \( \phi \) direction, but it also traverses in the anti-parallel direction in \( \theta \) space (e.g., \( \theta \simeq 180^\circ \) to \( \theta \simeq 0^\circ \)) due to damping (see (7)).

Note that at exactly \( \theta = 180^\circ \) or \( 0^\circ \), the torque acting on the magnetization due to interface anisotropy [equation (2)] is exactly zero, however, thermal fluctuations can scuttle the magnetization from these points to initiate switching. At the very start of switching, the initial orientation of magnetization is not a fixed value but rather a distribution due to thermal agitations. Such distribution is considered during simulations. Hence, thermal fluctuations affect the switching when magnetization starts to switch as well as during the course of switching.

The energy dissipated in the nanomagnet due to Gilbert damping can be expressed as \( E_d = \int_0^\tau P_d(t) \, dt \), where \( \tau \) is the switching delay and \( P_d(t) \) is the power dissipated at time \( t \) per unit volume given by

\[
P_d(t) = \frac{\alpha |y|}{(1 + \alpha^2)M} [T_I(t)]^2. \tag{9}
\]

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

3. Results

As depicted in figure 1, the nanomagnets (\( M_1 \) and \( M_2 \) layers) are made of Fe, while the ferroelectric P-layer is made of PbTiO\(_3\) [18, 27, 36, 37]. The spacer layer is made of Au and the thicknesses of the trilayer \( M_1/\text{spacer}/M_2 \) are 1/4/1 monolayers [18]. The Fe layer has a unit cell length of 0.287 nm and it has the following material parameters: saturation magnetization (\( M_s \)) = 1 \times 10^6 A m^-1, and damping parameter (\( \alpha \)) = 0.01 [38–40]. The elliptical lateral cross-section has a dimension of 15 nm \times 7 nm. The P-layer has a unit cell of length 0.388 nm and it has five layers in the
vertical direction ($x$ direction, figure 1) [18] while the lateral dimensions are the same as those of the nanomagnets. The energy difference between the P-alignment and AP-alignment is 10 meV/atom [18], and the absolute value of energy turns out to be about 10 eV or 385 kT at room-temperature. This huge interface coupling makes the potential landscape of $M_1$ monostable at $\theta = 180^\circ$ or at $\theta = 0^\circ$ depending on the P-alignment or the AP-alignment in the trilayer, respectively. Hence, no spontaneous switching of magnetization between $\theta = 180^\circ$ and $\theta = 0^\circ$ can take place. The shape anisotropic energy barrier is a few orders of magnitude lower than this interface coupling energy and thus consideration of shape anisotropy does not make any significant difference; however, it is included during the simulations.

Modelling the $P$-layer as a parallel plate capacitor and using a relative dielectric constant of 1000 [41], the capacitance $C$ of the layer becomes $\sim 0.4 \text{ fF}$. If the P-layer is accessed with a 10 $\mu$m long silver wire with resistivity $\sim 2.6 \mu\Omega \text{ cm}$ [42], the resistance $R$ becomes $\sim 3 \text{ k}\Omega$. Therefore, the $RC$ time constant is of the order of 1 ps. The ferroelectric PbTiO$_3$ has a coercive voltage of $20 \text{ MV m}^{-1}$ [43] and hence a voltage $V \approx 40 \text{ mV}$ is required to switch the polarization. (Note that the voltage required to switch the traditional charge based devices is of the order of 1 V [44].) Polarization switching is possible in less than 100 ps [45] and a voltage ramp with period $T = 100 \text{ ps}$ or more is considered to enforce the quasistatic (adiabatic) assumption ($T \gg RC$). Without any adiabatic assumption, the metric $CV^2$ is 0.5 aJ and hence the energy dissipation in the external circuitry that applies the voltage is miniscule. With 100 ps ramp period, the ‘$CV^2$’ dissipation becomes a negligible value of 0.01 aJ [9, 46]. Note that we do not calculate any leakage current through the thin ferroelectric since the device operation is non-volatile, i.e., it is possible to turn off the voltage without losing the information. Also, during the active mode of operation, the tunnelling current is small ($\leq 1 \text{ nA}$ [25]), leading to negligible energy dissipation. Note that ferroelectric fatigue may make the coercive field higher [47, 48], however, since the energy dissipation due to applied voltage is miniscule, it does not appear to be a bottleneck provided the polarization switches and the interface coupling between the P-layer and the trilayer still persists.

Figure 2 shows a sample dynamics of magnetization in the presence of room-temperature (300 K) thermal fluctuations. The ramp period is considered to be 100 ps and the switching has completed in less than 175 ps. During the course of switching magnetization has temporarily backtracked due to random thermal kicks; however, the strong interface anisotropy has enforced magnetization to switch from $\theta \approx 180^\circ$ to $\theta \approx 0^\circ$.

Figure 3 plots the average switching delay versus average energy dissipation for different ramp periods (0.1–1 ns). A moderately large number of simulations (100 000) in the presence of room-temperature (300 K) thermal fluctuations are performed to generate each point in the curve. When the magnetization reaches $\theta \leq 5^\circ$, the switching is deemed to have completed. Note that as the applied voltage across the heterostructure is ramped at a slower rate, the switching also gets slower and less energy is dissipated in the switching process, elucidating the delay–energy trade-off for the device. The results show that switching with sub-nanosecond delay is plausible while dissipating an energy of only $\sim 1 \text{ aJ}$. The ‘$CV^2$’ energy dissipation is a couple of orders of magnitude lower than the energy dissipation due to Gilbert damping and it decreases with the increase of ramp period since the switching becomes more adiabatic. The standard deviation of the switching delay for a ramp period of 0.1 ns is about 22 ps and it increases about twice when the ramp period is increased to 1 ns. At higher ramp period, thermal fluctuations have more time to scuttle the magnetization and cause variability in switching time. Simulations have been performed at an elevated temperature (400 K) and the performance metrics, switching delay and
energy dissipation turn out to be similar (within 5%) compared to that of the room-temperature (300 K) case. See the online supplementary material for additional simulation results (stacks.iop.org/JPhysD/47/252002/mmedia).

4. Discussions

The giant magnetoresistance (GMR) [49, 50] of the trilayer in this interface-coupled structure is calculated to be of the order of 30% [18, 51], which provides a way to read the magnetization states (P-alignment or AP-alignment). Although this GMR is not that high compared to tunnelling magnetoresistance (TMR) [52–56], suitable design strategies can possibly be devised to work with this moderate value of GMR and also it may be possible to increase the GMR by way of suitable material choice and design. It is also argued that even with the variance in the smaller thicknesses of the layers, it is still possible to interface-couple the polarization and magnetization in the proposed structures [18]. The modelling of interface anisotropy is not limited to the method performed here; however, any strong interface-coupled system would facilitate the switching of magnetization from one state to another.

Due to the small lateral dimensions of these interface-coupled multiferroic heterostructures, it is possible to cram an enormous amount of devices on a single chip. Using an area density of $10^{-12} \text{cm}^{-2}$, the dissipated power would be $10 \text{mW cm}^{-2}$ considering 1 A energy dissipation in a single nanomagnet with 1 ns switching delay and 10% switching activity (i.e., 10% of the magnets switch at a given time). Such extremely dense and ultra-low energy non-volatile computing systems can be powered by energy harvesting systems [57–60].

5. Conclusions

In conclusion, we have performed an analysis of the switching dynamics of magnetization in interface-coupled multiferroic magnetoelectrics. We have modelled the interface anisotropy and calculated the performance metrics e.g., switching delay and energy dissipation as a function of ramp period to elucidate the delay–energy trade-off. The results show that switching can take place with a sub-nanosecond switching delay while expending $\sim 1 \text{A fJ}$ of energy. Also, strong interface coupling facilitates error-resilience during the switching and allows us to scale down the lateral area to very small dimensions. Due to these superior performance characteristics of interface-coupled multiferroics, it would be of immense interest to work out different possible theoretical designs and experimental implementations. Successful experimental implementations must tackle the issue of process variation at low dimensions. Processors built on such platforms could presage unprecedented applications that could work by harvesting energy from the environment e.g., a medically implanted device to warn of an impending epileptic seizure by monitoring the brain signals, or wearable computers powered by body movements etc.

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