Electric field driven multi-state magnetization switching in triangular nanomagnets on piezoelectric substrate

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Abstract
Electric field control of magnetic state switching mediated by magneto-elastic coupling in multiferroic heterostructures consisting of shape anisotropic magnetostrictive nanomagnets elastically coupled with a piezoelectric substrate has a promising potential for next generation magneto-elastic memory and logic devices. In this work, by using micromagnetic simulation, we showed that localized strain-induced magnetic anisotropy caused by the electric field-induced piezostrain combined with strong multifold shape anisotropy effect can be used for achieving a multistate switching of magnetization in a triangular soft magnetic nano-island on a piezoelectric substrate. A piezostrain-induced uniaxial magnetic anisotropy pulse applied in specific directions switches the magnetization within the triangular nanomagnet by an angle of 60° from the initial state. The relation between critical magnitude of the strain pulse for the switching of the magnetization states and geometric parameters (thickness and lateral size) within the triangular nanomagnets has been worked out. Complete cycles of clockwise as well as counter-clockwise switching of the magnetization states of the triangular nanomagnet have been achieved by a series of sequential switching with different directions of applied strain-induced magnetic anisotropy. This local gating scheme-based multistate switching can be used for electric field-induced ultra-fast, deterministic and reversible magnetization switching which are the key challenges in designing of the magnetoelastic and/or magnetoelectric memory and logic devices.

Keywords: magnetization switching, micromagnetic simulation, electric field-induced magnetic anisotropy, multiferroic heterostructures

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

1. Introduction
Current-induced magnetic field \cite{1}, spin-polarized current based spin-transfer \cite{2} or spin–orbit \cite{3} torque, spin Hall effect \cite{4} and interface engineering including interfacial control of so called Rashba spin–orbit interaction \cite{5, 6} and exchange coupling at ferroelectric/ferromagnet interface \cite{7, 8} are the driving forces in commonly implemented schemes for magnetic state switching at nanoscale. In straintronics, multiferroic heterostructures consisting of shape anisotropic magnetostrictive nanomagnets elastically coupled with a piezoelectric substrate can be used for electric field-induced robust, reversible and repeatable magnetization switching \cite{9–11}. The magneto-elastic switching is based on the magnetic moment precession caused by the uniaxial mechanical stress/strain resulting from the applied voltage across the
piezoelectric layer, the so-called converse piezoelectric effect. It has been theoretically predicted as well as experimentally proved that the device based on strain mediated electric field-induced magnetization switching is much energy efficient than conventionally implemented schemes for this purpose [12–15]. This scheme holds a promise in elimination of the factors including sophisticated device architecture, high energy consumption and energy dissipation caused by Joule heating effect which are usually present in current-induced magnetic switching devices. That is why much effort has been devoted for the research and development in this field.

In multiferroic nanostructures, the primacy size and surface effect brings about some remarkable features that may favor the electric field control of magnetization, including atomic scale mechanical coupling, suppression of the substrate clamping effects and significant shape anisotropy [16]. Various experimental demonstrations have been done in this novel pathway by utilizing the size effect in controlling the magnetism by using electric field [17–19]. For instance, triangular shaped ferromagnetic nano-island is an ideal candidate for magneto-elastic type of switching scheme due to its advantage of multi-fold shape anisotropy [20]. Recently, it was shown by Yao et al, with a detailed experimental demonstration that this kind of nanostructure is very much suitable for robust and reversible switching between two neighboring states different by an angle of 120° in magnetization orientation by applying voltage directly to the nanomagnet without the assistance of an external magnetic field [21]. The researchers reported the magnetization switching in an array of Co triangular nanomagnets deposited on bismuth ferrite (BFO) film and proposed a combined effect of piezostrain, interfacial exchange coupling and shape anisotropy to be the underlying mechanism. BFO is known to be a room temperature multiferroic. A brief summary of the properties and applications of this material can be found in [22].

Alternatively, electric field-induced anisotropy manipulation of the in-plane magnetization switching in multistate memory units based on such shape anisotropic nanostructures can also be achieved by strain mediated schemes [23, 24]. For instance, in one of this kind of configuration a set of electrode pairs enclosing the ferromagnetic nanostructure is deposited on a piezoelectric substrate. Activation of an electrode pair by the application of suitable electric field generates biaxial mechanical stresses pulse on the piezoelectric substrate and simultaneously transfers to the magnetostrictive ferromagnetic nanostructure thus leading to the magnetic states switching. Such local gate strategy proven to be effective in electric field switching of both magnetic states and magnetoresistance behaviors in magnetic tunnel junction device, showing promising prospect for exploiting it in magnetic memory devices [25].

Figure 1. (a) Schematic illustration for obtaining the triangular geometry inside an array of three closely packed spheres along with the description of the lateral dimension considered in simulation. (b) Proposed device structure consisting of a triangular nanomagnet enclosed by three electrodes residing on a piezoelectric substrate with a grounded bottom electrode. (c) Description of the angle θ used for the quantitative analysis of the in-plane magnetization rotation calculated from the simulated configuration (magnetization vector map) for the triangular nanomagnet using simple vector algebra. In-plane orientation of moments within the magnetization vector map is represented by the color wheel. Colored arrows shown on the vertices of the triangular geometry mark the average magnetization vectors. The yellow arrow at the center shows the direction of net in-plane magnetization vector (Mnet).
The top right of the image.

In-plane orientation of moments within the magnetization vector map is represented by the color wheel at the top right of the image.

Figure 2. Estimated magnitude of the critical electric field-induced strain ($\Delta \varepsilon_{\text{c}}$) as a function of (a) lateral dimensions and (b) thickness of the triangular nanomagnet. Thickness used in (a) is 20 nm while the lateral dimension used in (b) is 500 nm. (c) Estimation of the critical switching strain ($\Delta \varepsilon_{\text{s}}$) for a 60° in-plane magnetization after and before switching. In-plane orientation of moments within the magnetization vector map is represented by the color wheel at the top right of the image.

In this work, we demonstrate the electric-field manipulation of the multistate magnetization switching within a triangular shaped isolated nanomagnet by means of the micromagnetic simulation and based on the local piezostrain strategy a schematic design for such switching device suitable for deterministic and reversible control of magnetization has been suggested. The assumed system is composed of a soft magnet in the shape of triangular nano-island enclosed by three electrodes and mechanically coupled with a piezoelectric substrate. Electrodes were considered to work in the form of pairs in order to generate a localized and anisotropic strain in underlying piezoelectric layer. The proposed design offers simple device architecture that may be useful for individually addressable and non-volatile multistate magnetoelectric or magnetoelastic memory and logic device applications.

2. Micromagnetic simulation

The system considered for simulation study is shown in figure 1. It consists of a triangular nano-island whose shape was determined from the triangular geometry inside the three closely packed nano-spheres, as shown in figure 1(a). This triangular nanomagnet is considered to be surrounded by three electrodes such that each electrode is facing one of the three sides of the triangle. The whole set of architecture is assumed to be deposited on a piezoelectric substrate, as shown in figure 1(b). Two dimensional solver of the object oriented micromagnetic framework (OOMMF) software package, in which time dependent evolution of magnetization is obtained by solving the well-established Landau–Lifshitz–Gilbert ordinary differential equation [26], is used for the simulation. The magnetic material parameters corresponding to Co i.e. saturation magnetization $M_s = 1.4 \text{ MA m}^{-1}$ and exchange stiffness $A_{ex} = 30 \text{ pJ m}^{-1}$ are assumed for the triangular nanomagnet whose dimensions are also shown in figure 1(a). Damping parameter and the mesh size are chosen to be 0.05 [21] and $5 \times 5 \text{ nm}^2$ respectively. To simulate the time sequence evolution of the magnetic states, a smaller damping factor of 0.005 [27] is also employed to give a more accurate estimation of the simulation time.

Following ordinary differential equation known as Landau–Lifshitz equation is integrated in 2D solver of the OOMMF software package [26]:

$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \frac{\gamma \alpha}{M_s} \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{\text{eff}})$$

(1)

where $\mathbf{m}$, $\mathbf{H}_{\text{eff}}$, $M_s$, $\gamma$ and $\alpha$ are the magnetization, effective field, Landau–Lifshitz gyromagnetic ratio and the damping coefficient respectively.

The effective field $\mathbf{H}_{\text{eff}}$ in above equation is related to the average energy density also called the free energy density ($E_{\text{f}}$) which includes anisotropy ($E_{\text{anis}}$), exchange ($E_{\text{exch}}$), demagnetization ($E_{\text{demag}}$) and Zeeman energy ($E_{\text{Z}}$) terms. An externally applied electric field produces a strain-induced magnetic anisotropy ($K_s$) which contributes to the anisotropy energy term of the free energy formalism.

The strain-induced magnetic anisotropy ($K_s$) resulting from the strain ($\Delta \varepsilon$) generated in response to the applied electric field across the piezoelectric layer is given as [28]:

$$K_s = \frac{3\lambda Y}{2(1+\nu)} \Delta \varepsilon$$

(2)

where $Y$, $\lambda$ and $\nu$ being the Young’s modulus, magnetostriction coefficient and the Poisson’s ratio respectively while $\Delta \varepsilon = \varepsilon_{xx} - \varepsilon_{yy}$ is from the electric field-induced strain. The process of electrode activation is simulated by the application of a negative value $K_s$ pulse. In order to switch the magnetization orientation in the nanomagnet away from its initial direction a negative value $K_s$ pulse is required to make the direction of applied $K_s$ a hard axis [26]. The parameters corresponding
to Co (ferromagnetic) i.e. $Y = 209$ GPa, $\lambda = 6 \times 10^{-5}$ and $\nu = 0.32$ were considered in order to roughly estimate the magnitudes of strain from the values of $K_s$ used in the simulation.

3. Results and discussion

In order to simplify the quantitative analysis of the in-plane magnetization rotation, an angle ($\theta$) can be defined as the angle subtended by the net magnetization vector ($\mathbf{M}_{\text{net}}$) with $x$-axis, as shown in figure 1(c), which can easily be calculated by using simple vector algebra with the rectangular components of the normalized magnetization. Co triangular nano-island may prefer one of the shape anisotropy-mediated six different magnetic states, in which the direction of $\mathbf{M}_{\text{net}}$ may either be towards one of the vertices or towards one of the sides of the triangular shape i.e. along the easy axis. Because each electrode is facing one side of the triangle therefore the line joining any of the electrode pairs is parallel to one of the sides of the triangular shape and hence makes an angle of $\theta \pm 30^\circ$ with the $x$-axis i.e. along the hard axis. Activation of an electrode pair i.e. applying electric field is supposed to produce a uniaxial mechanical strain in the piezoelectric layer along the line joining the electrodes via converse magnetoelectric effect which can then be transferred to the triangular ferromagnetic nano-island via interfacial mechanical coupling, resulting in magnetization switching through magnetostriction.

First of all, the dependence of the critical electric field-induced strain ($\Delta \varepsilon_c$ the minimum magnitude of the strain) required to switch the magnetization orientation of the triangular nanomagnet, on both the lateral size and thickness of the nanomagnet is studied. For each size an initial state was obtained by the step wise application and removal of an in-plane magnetic field of 0.2 T along $x$-axis to the triangular nanomagnet with initial random magnetic configuration. The critical strain for triggering of a $60^\circ$ magnetization switching was estimated by monitoring the evolution of $\mathbf{M}_{\text{net}}$ orientation

![Figure 3](image-url)  
Figure 3. Magnetization vector maps (top) for the switching dynamics with temporal evolution (bottom) of normalized magnetization components and hence angle ($\theta$) during a $60^\circ$ counter-clockwise rotation of in-plane magnetization ($\mathbf{M}_{\text{net}}$) of the triangular nanomagnet in response to the applied $K_s$ pulse (corresponding strain ($\Delta \varepsilon$) is shown in the middle panel) in the direction shown by the blue double headed arrow on the black triangular geometry lying between the initial and intermediate states. In-plane orientation of moments within the magnetization vector map is represented by the color wheel at the top right of the image.
as a function of strain pulse, shown in figure 2(c) in order to find out the critical value for the different dimensional parameters of the nanomagnet.

Figures 2(a) and (b) shows the variation of critical strain ($\Delta \varepsilon_c$) with nanomagnet’s lateral dimensions and thickness respectively. The magnitude of the critical strain ($\Delta \varepsilon_c$) is found to vary with the variation in size of the nanomagnet. Larger magnitude of the strain ($\Delta \varepsilon_c$) is required for magnetization switching in larger nanomagnet either in in-plane dimension or out-of-plane dimension. However, thinner nanomagnets require smaller strain for switching of the magnetization within them even if their in-plane dimensions are large [29].

For example, the minimum magnitude of the strain required to switch the magnetization in a nanomagnet of lateral dimension 500 nm with thickness 20 nm is found to be $\Delta \varepsilon_c \approx 1.43\%$ below which the magnetization orientation remained unchanged or showed an incomplete switching and a much smaller ($\Delta \varepsilon_c \approx 0.13\%$) is obtained in a much thinner nanomagnet (~2 nm) even with same lateral size. It is also noted that if the in-plane or out-of-plane size is too large, the nanomagnets would show a steady state in the form of a vortex which makes the magnetization state unable to switch and this limits the dimensions of the nanomagnet to less than 50 nm in thickness and below 1 $\mu$m in lateral size.

In other words it can be said that the energy barrier between adjacent magnetization states within the triangular nanomagnet can be modified by the size and shape variation of the memory element. Overcoming the small energy barrier requires less magnitude of the applied electric field and vice versa. In general, smaller lateral size and thickness requires lower critical strain.

The representative switching dynamics for a $\Delta \theta \sim 60^\circ$ counter-clockwise switching in triangular nanomagnet of size 500 nm are shown in figure 3. Initially the magnetization orientation within the triangular nanomagnet ($M_{\text{init}}$) is oriented at $\theta \sim 45^\circ$ from the $x$-axis (first image in the top panel of figure 3). In response to the applied $K_e$ pulse (corresponding strain $\Delta \varepsilon$ is shown in the middle panel of figure 3) in the direction making an angle $\sim 15^\circ$ (i.e. $\theta \sim 30^\circ$) with the $x$-axis. As a result the magnetization rotates counter-clockwise i.e. away from the initial direction, to an intermediate state (second image in the top panel of figure 3) which then relaxes into the final magnetization with $M_{\text{init}}$ at $\theta \sim 105^\circ$ from the $x$-axis.
Temporal evolution of the in-plane and out-of-plane components of the normalized magnetization is shown in the bottom panel of the figure 3. A minor fluctuation in these components at the instance of the front-edge of the applied pulse is seen after which they settle to a stable magnitude. As mentioned earlier that the angle \( \theta \) can be calculated by simple vector algebra with rectangular components of the normalized magnetization. The magnetization vector maps and the curve for \( \theta \) clearly show a \( \Delta \theta \sim 60^\circ \) counter-clockwise switching of the magnetization within the triangular nanomagnet.

Before starting the switching cycle an initial state is obtained by the step wise application and removal of an in-plane magnetic field of 0.2 T along x-axis to the triangular nanomagnet with initial random magnetic configuration. Next, for each step of 60° rotation, \( K_x \) pulse is applied in the direction with an angle of \( \theta + 30^\circ \) for clockwise and \( \theta - 30^\circ \) for counter-clockwise rotation of the initial in-plane magnetization orientation. This applied strain-induced magnetic anisotropy (\( K_x \)) pulse switches the initial magnetization within the triangular nanomagnet to an intermediate state which then relaxes into the next final state which differs from the previous state by an angle \( \Delta \theta \sim 60^\circ \). Temporal evolution of in-plane normalized components in terms of angle (\( \theta \)) is shown in the upper panels of figures 4(b) and (d) while that of out-of-plane normalized component is shown in lower panels of these figures. Solid and dotted vertical lines in upper panels of these figures are indicating the instances of front and back-edges of the applied pulses on the x-axis respectively. It can be seen that the out-of-plane component of the normalized magnetization shows slight fluctuations at the instances of applied pulses. It means that the switching form one in-plane orientation to the other is somehow mediated by small out-of-plane flipping of the magnetic moments within the triangular nanomagnet.

However in the schematics proposed here, the application of electric field generates a mechanical strain in the piezoelectric substrate via the converse piezoelectric effect [23]. The transfer of this electric field-induced mechanical strain to the magnetostrictive ferromagnetic nanostructure produces a stress anisotropy energy which contributes to the uniaxial anisotropy [30]. This localized modulation of the magnetic anisotropy or also called strain-induced magnetic anisotropy (\( K_x \)) results in the switching of the magnetic state within the nanomagnet.

Since it is discussed earlier that the rotation direction of the in-plane magnetization within the triangular nanomagnet depends on the direction in which the strain-induced magnetic anisotropy (\( K_x \)) is applied therefore proper choice of the direction for the application of electric field is important in order to achieve clockwise or counter-clockwise rotation of the magnetization. For example, let us assume an initial magnetization state of the triangular nanomagnet in which \( \mathbf{M}_{\text{net}} \) has \( \theta \sim 45^\circ \). The magnetization switched \( \Delta \theta \sim 60^\circ \) clockwise in response to the strain-induced magnetic anisotropy (\( K_x \)) applied in a direction making an angle \( \sim 75^\circ \) with the x-axis i.e. \( \theta + 30^\circ \) and counter-clockwise when the applied \( K_x \) is in the direction with angle \( \sim 30^\circ \) from the x-axis i.e. \( \theta - 30^\circ \). This in fact makes the switching scheme deterministic and reversible because one can control the switching process by just selecting the suitable electrode pair for activation.

4. Conclusion

By using micromagnetic simulation we studied the multi-state switching of magnetization in a triangular shaped soft magnet nano-island on a piezoelectric substrate. The localized electric field-induced magnetic anisotropy mediated by local piezostrain scheme combined with strong multifold shape anisotropy effect has been theoretically implemented for deterministic and reversible magnetization switching. Critical magnitude of the electric field-induced strain for the switching of the magnetization states by 60° within different in-plane and out-of-plane sized triangular nanomagnets has been investigated. Moreover, complete cycles of clockwise as well as counter-clockwise switching of the magnetization states within the triangular nanomagnet has been achieved. An electric field-induced effective anisotropy pulse with a constant magnitude is used throughout the switching cycles. This study can help the field of ultra-fast, deterministic and reversible magnetoelastic memory and logic devices designing to get a step forward.

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