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ORIGINAL REPORT

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Switching the chirality of a magnetic vortex deterministically with an electric field

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ABSTRACT

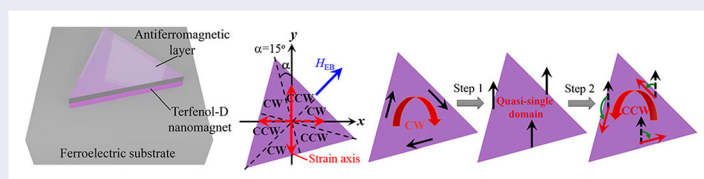
Deterministic switching of a magnetic vortex with an electric field is challenging because electric fields cannot break time-reversal symmetry. Here we demonstrate, using phase-field simulations, a deterministic switching of the vortex chirality in a triangle-shaped nanomagnet by applying an electric field to its underlying ferroelectric layer. The nanomagnet is juxtaposed with an overlying antiferromagnetic layer to acquire an exchange bias from their interface. The simulations show that such deterministic electrically-driven magnetic vortex chirality switching is enabled by a synergistic effect of the electric-field-induced strain from the ferroelectric, the three-fold in-plane shape anisotropy of the nanomagnet, and the exchange-bias field.

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KEYWORDS

Vortex chirality switching; nanomagnets; ferroelectric; phase-field simulations



IMPACT STATEMENT

An electric-field-controlled deterministic switching of magnetic vortex chirality has been computationally demonstrated in a novel magnetoelectric architecture, offering a viable route to designing low-power vortex-based spintronic devices.

1. Introduction

Magnetic vortex is a swirling spin configuration that can be characterized by the chirality of the in-plane magnetization vector (i.e. clockwise (CW) or counterclockwise (CCW)) and the polarity of the vortex core (up or down) [1–3]. It can potentially be used to design a four-state memory [3] which encodes bit information based on both the vortex chirality and core polarity.

Controlling magnetic vortices has attracted much attention over the past decade. Switching the vortex core polarity has been realized by applying a static [4] or dynamic [5] magnetic field. Attempts have also been

made to switch the vortex chirality deterministically by lifting the degeneracy between the CW and CCW chirality through the use of a bias magnetic field in shape-engineered nanomagnets [6,7], a spatially variant magnetic field [8], and ultrafast magnetic field pulses [3,9].

Here we demonstrate a deterministic switching of the vortex chirality with electric fields, which is more desirable for applications than magnetic fields because an electric-field is non-power-dissipating and easier to localize on a chip. Although electric-field-controlled magnetization switching has been demonstrated via different routes in different materials systems [10–13],

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research into electric-field-controlled switching of magnetic vortices has not appeared until recently [14–16]. For example, vortex chirality switching has been experimentally observed in micron-sized Co disks by applying electric field to (011)-Pb(Mg_{1/3}Nb_{2/3})O₃-PbTiO₃ substrates, but the chirality switching is not deterministic [14]. To our knowledge, an electric-field-controlled deterministic switching of magnetic vortex chirality has not yet been reported.

In this letter, we computationally achieved the electric-field-controlled deterministic switching of magnetic vortex chirality through heterostructure design. Figure 1(a) shows the proposed heterostructure consisting of an equilateral-triangle-shaped amorphous nanomagnet sandwiched by an underlying ferroelectric layer and an overlaying nanoscale antiferromagnet. Using phase-field simulations, we show that an electric-field-controlled deterministic switching of magnetic vortex chirality can be achieved in such heterostructure through a synergistic effect of a strain-mediated electric-field-induced uniaxial magnetic anisotropy, the three-fold magnetic in-plane shape anisotropy in the triangle-shaped nanomagnet [17], and a Zeeman-type magnetic anisotropy from the interfacial exchange-bias field.

2. Methods

In the phase-field model, the local magnetization vector $\mathbf{M}$ is the main order parameter, the spatial distributions of which represent magnetic domain structures. The temporal evolution of the local magnetization vector $\mathbf{M}$ can be described by the Landau-Lifshitz-Gilbert equation,

$$(1 + \alpha^2) \frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 (\mathbf{M} \times \mathbf{H}_{\text{eff}}) - \frac{\gamma_0 \alpha}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}}) \quad (1)$$

where γ_0 and α represent the gyromagnetic ratio and the Gilbert damping coefficient, respectively. Equation (1) was solved using a semi-implicit Fourier spectral method [18] using a small time step Δt of about 0.1 ps. The effective magnetic field is $\mathbf{H}_{\text{eff}} = -(1/\mu_0)(\delta F_{\text{tot}}/\delta \mathbf{M})$, where μ_0 denotes the vacuum permeability; F_{tot} is the total magnetic free energy of the amorphous nanomagnet, given as,

$$F_{\text{tot}} = \int_V (f_{\text{stray}} + f_{\text{exch}} + f_{\text{EB}} + f_{\text{elastic}}) dV \quad (2)$$

where f_{stray} , f_{exch} , f_{EB} and f_{elastic} are stray field, Heisenberg exchange, exchange-bias-related and elastic energy densities, respectively. For an exchange bias field (H_{EB}) aligning at 45° to the x -axis in the xy plane, f_{EB} is written as $f_{\text{EB}} = -H_{\text{EB}} M_s \left[\frac{\sqrt{2}}{2} (m_x + m_y) - 1 \right]$. The expressions

for f_{stray} , f_{exch} and f_{elastic} of the nanomagnet are given in Ref. [19].

Three-dimensional grids of $154\Delta x \times 154\Delta y \times 60\Delta z$ with real grid sizes $\Delta x = \Delta y = 2.0$ nm and $\Delta z = 3.8$ nm were employed to describe a three-phase system consisting of the ferroelectric layer ($= 45\Delta z$), the triangle-shaped nanomagnet ($= 10\Delta z = 38$ nm), and the surrounding vacuum. The nanoscale antiferromagnet was not described by grids. The influence of the side length (L) and thickness (d) of the nanomagnet on vortex chirality switching is studied by changing the grid size (Δx , Δy , Δz) or the number of grids. Amorphous Terfenol-D with giant magnetostriction ($\lambda_s \sim 320$ ppm [20]) is considered as an exemplary magnetic material. Relevant materials parameters used in simulations are: the saturated magnetization $M_s = 8 \times 10^5$ A/m [18]; elastic stiffness coefficients $c_{11} = 141$ GPa, $c_{12} = 64.8$ GPa, and $c_{44} = 38.1$ GPa [18]; $\alpha = 0.06$ [21]; $\gamma_0 = 2.43 \times 10^5$ m/(A·s) [22]; the exchange coefficient $A_{\text{ex}} = 9 \times 10^{-12}$ J/m [21]. BaTiO₃ single crystal [23] or Bi₂WO₆ film [24] that can generate large electric-field-induced strain through non-180° ferroelectric domain switching are possible candidates for the ferroelectric layer. This work focuses on a computational identification of the critical strain required to switch the vortex chirality, and the dynamic process of generating strain upon applying a voltage is not studied for simplicity.

3. Results and discussion

As shown in Figure 1(b), the triangle geometric symmetry axis is aligned at an angle α ($= 15^\circ$) to the $+y$ axis, which ensures that the critical strains required for the CW-to-CCW switching and CCW-to-CW switching have the same magnitude. The three-fold in-plane magnetic shape anisotropy can be seen from the distribution of f_{stray} of the initial CW vortex in Figure 1(d). The initial CW chirality of magnetic vortex can be obtained by applying a magnetic field along the $+x$ axis to form a uniformly magnetized domain, and then removing the magnetic field. Switching the vortex chirality via electric-field-induced strain involves two dynamic processes as schematically shown in Figure 1(c): (i) applying a uniaxial strain along the y -axis to transform the vortex to a buckle-like domain, which is enabled through the co-action of the H_{EB} and strain-induced uniaxial magnetic anisotropy along the y -axis; (ii) removing the uniaxial strain leads to the nucleation of a vortex state driven by the minimization of the stray field energy. Notably, depending on the magnetization orientation in intermediate buckle-like domain, the equilibrium vortex chirality

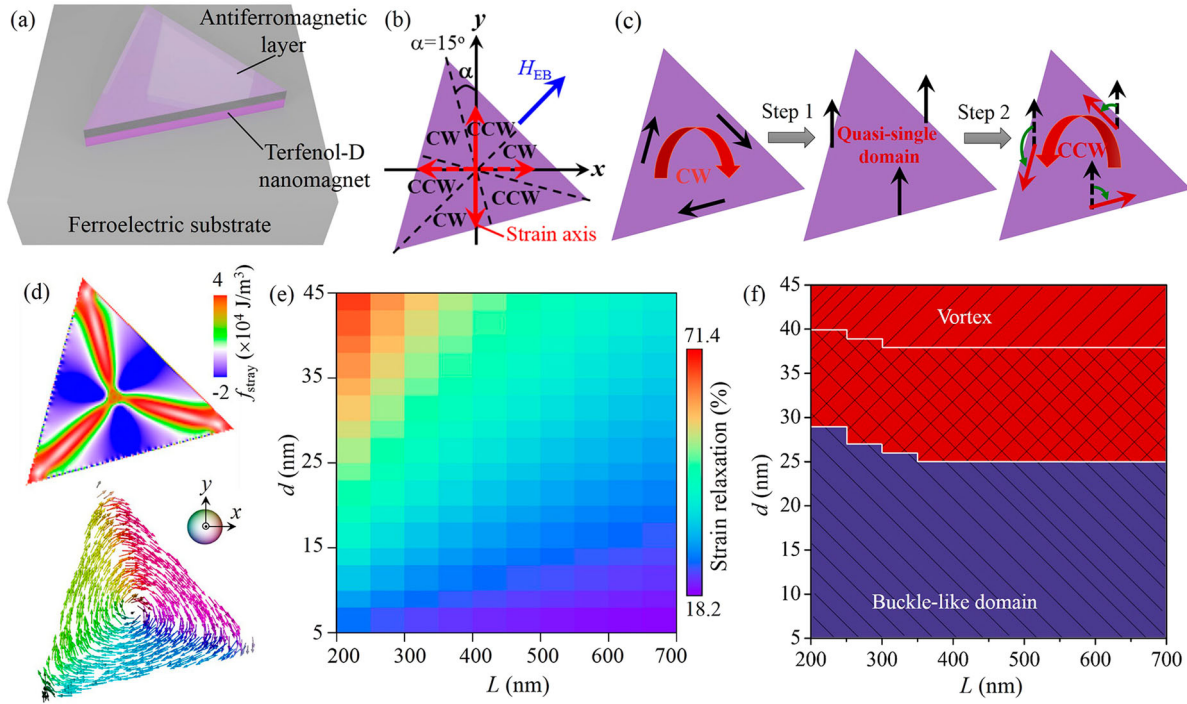


Figure 1. (a) Schematic of the proposed heterostructure. (b) Top view of the triangle-shaped nanomagnet titled by 15° to the $+y$. (c) A two-step mechanism of switching the vortex chirality from CW to CCW. (d) Distribution of the f_{stray} for a CW vortex with $H_{\text{EB}} = 0$, where the color wheel denotes the direction of local magnetization. (e) the degree of strain relaxation ($= 1 - (\varepsilon_{\text{ave}}/\varepsilon_{\text{app}})$) as a function of the side length (L) and thickness (d) of the nanomagnet. ε_{ave} is the volume average of the actual strain in the nanomagnet, while ε_{app} is the applied strain. (f) Phase-diagram of the initial magnetic states with $H_{\text{EB}} = 120$ Oe as a function of L and d . Only one state (either vortex or buckle-like domain) exists wherever there is only one type of pattern. The two states coexist in regions where two line patterns overlap. Note that the vortex and the buckle-like domain are stable (ground-state) and metastable, respectively, in the overlapping region. The ground state is also colored red (for vortex) and blue (for buckle).

can be either CW or CCW (see Figure 1(b)) due to the asymmetric nucleation energy of these two vortex states [6] (also see Figure S1).

Strain applied onto such triangle-shaped nanomagnet will relax along the edges due to the stress-free lateral surfaces. The degree of strain relaxation is smaller in triangle magnets with larger side length L and smaller thickness d (see Figure 1(e)). Figure 1(f) presents the thermodynamic stability both the buckle-like domain and vortex under different L and d . As seen, the formation of a buckle-like domain (vortex) is favored driven by the minimization of exchange energy (stray field energy) under relatively small (large) d and L . There are two criteria of choosing the L and d for the proposed strain-mediated vortex chirality switching. First, the degree of strain relaxation needs to be low in order to make the best use of the applied strain. Second, the vortex state and the buckle-like domain should be thermodynamically stable and metastable, respectively, under the given L and d . Based on these two criteria, L and d were set as 300 nm and 38 nm, respectively. This will yield the smallest applied strain for a deterministic vortex chirality switching.

Figure 2(a) shows an electrically-controlled vortex chirality switching in the triangle nanomagnet ($L = 300$ nm, $d = 38$ nm) enabled by a square-shaped bipolar strain pulse. Figure 2(b) correspondingly shows the surface magnetization distribution at different stages. The H_{EB} is taken as 120 Oe to reduce the critical strain for the switching (discussed later). When an electric-field-induced tensile uniaxial strain ($\varepsilon_{yy} = 4300$ ppm) is applied, a uniaxial magnetic anisotropy along the y axis is created due to the positive magnetostriction. Driven by both the H_{EB} and the strain-induced uniaxial magnetic anisotropy, the core of the initial CW vortex gradually moves out of the triangle largely along the $+x$ direction (see bottom panel of Figure 2(a) and Figure S3(a)), forming a buckle-like domain (state ②). Because local magnetization vectors mostly lie within the CCW region (c.f., Figure 1(b)), the formation of a CCW vortex is energetically favorable after removing ε_{yy} (state ③). Such a switching is non-volatile because in-plane shape anisotropy prevents the backward switching of the CCW vortex to the buckle-like domain (see Figure S1). A subsequent application of a compressive strain ($\varepsilon_{yy} = -4300$ ppm) pulse can likewise switch the CCW

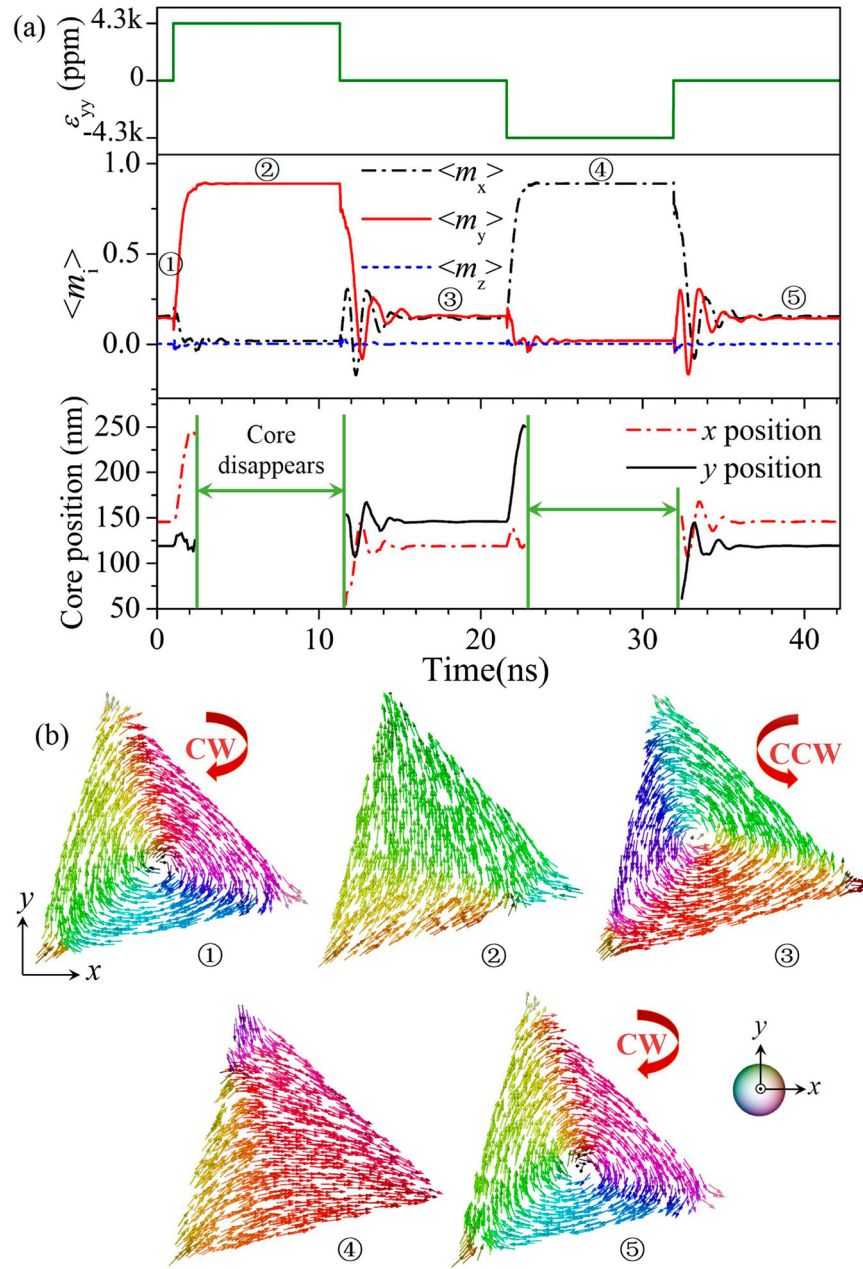


Figure 2. (a) An electric-field-induced strain pulse (ε_{yy}) with a duration of 10.30 ns along the y axis (top panel) enabling vortex chirality switching, temporal evolution of the average magnetization component $\langle m_i \rangle$ ($i = x, y, z$) (middle panel) and temporal trajectories of vortex core (bottom panel). (b) Stable surface magnetization distributions corresponding to states ①–⑤.

to the CW vortex via an intermediate buckle-like domain (state ③–⑤). Vortex chirality switching by a faster strain pulse (~ 5 ns) was also simulated (see Figure S4).

Now turn to discussing how the size (L and d) of the triangle magnet and the H_{EB} influence the critical strain for the vortex-to-buckle switching. Under the same thickness $d = 38$ nm, the critical applied strain ($\varepsilon_{crit,appl}$) changes non-monotonically yet becomes larger overall as L increases in Figure 3(a). When L is small (e.g. 250 nm), the degree of strain relaxation is large,

requiring larger $\varepsilon_{crit,appl}$. When L is relatively large (e.g. 600 nm), the degree of strain relaxation is small, but the vortex state becomes more stable due to the minimization of stray field energy. Thus, larger $\varepsilon_{crit,appl}$ is still required to switch it to the buckle-like domain. However, $\varepsilon_{crit,appl}$ exists a minimum value of about 4600 ppm at $L = 300$ nm, at which the degree of strain relaxation is smaller than that of 250 nm yet the stability of the initial vortex state is smaller than that of 600 nm. Despite such complex feature, the actual critical

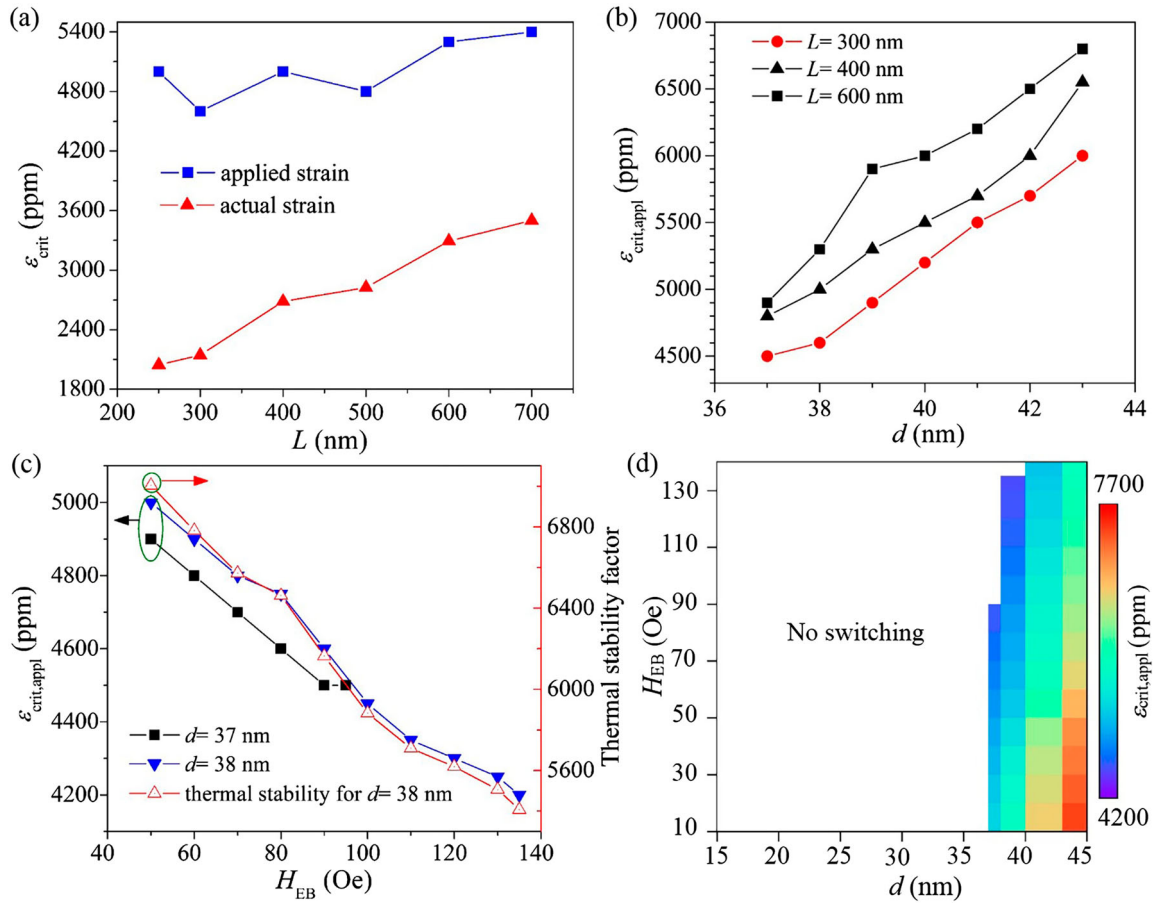


Figure 3. (a) Effect of L on critical strain for switching vortex to buckle-like domain at $d = 38$ nm and $H_{\text{EB}} = 90$ Oe. (b) Effect of d on $\varepsilon_{\text{crit,appl}}$ at $H_{\text{EB}} = 90$ Oe for $L = 300$ nm, 400 nm, 600 nm. H_{EB} is taken as 90 Oe in (a-b) to stabilize the vortex state under a relatively small L (e.g. 250 nm). (c) Effect of H_{EB} on $\varepsilon_{\text{crit,appl}}$ and thermal stability factor under a constant L (300 nm) but different d . (d) Influence of H_{EB} and d on the magnitude of $\varepsilon_{\text{crit,appl}}$ (color bar) at $L = 300$ nm. When H_{EB} and d fall within the white region, the vortex chirality switching cannot occur because vortex state would not be stable.

strain (subtracting the relaxed strain from $\varepsilon_{\text{crit,appl}}$) increases with L solely due to the enhanced vortex stability.

Under three different L (300 nm, 400 nm, and 600 nm), a monotonic increase of $\varepsilon_{\text{crit,appl}}$ with d is found (Figure 3(b)), as a consequence of both the enhanced vortex stability and the larger degree of strain relaxation. When L and d are fixed at 300 nm and 38 nm, respectively, $\varepsilon_{\text{crit,appl}}$ decreases from 5000 ppm to 4200 ppm with H_{EB} increasing from 50 Oe to 135 Oe (Figure 3(c)). This is because H_{EB} can reduce the stability of the initial vortex state, thereby facilitating the switching. Indeed, the thermal stability factor ($= \Delta E_{\text{barrier}} V_{\text{m}} / k_{\text{B}} T$) for the initial vortex decreases from 7004.2 to 5407.6 with H_{EB} increasing from 50 Oe to 135 Oe at $d = 38$ nm. This results from the decrease of $\Delta E_{\text{barrier}}$, where $\Delta E_{\text{barrier}}$ is the energy density barrier of vortex chirality switching (see Figure 4(a)). V_{m} is the volume of the nanomagnet, k_{B} Boltzmann constant and $T = 300$ K the temperature. If the

H_{EB} is too large, the initial vortex would no longer be stable, and the corresponding threshold of H_{EB} varies with the thickness d . The influences of the H_{EB} and d on the $\varepsilon_{\text{crit,appl}}$ are summarized in Figure 3(d). When H_{EB} and d fall into the white region in Figure 3(d), the vortex state cannot stably exist.

Figure 4(a) shows the energetics for vortex chirality switching under the application of $\varepsilon_{\text{yy}} = 4300$ ppm, where L , d , and H_{EB} are 300 nm, 38 nm, and 120 Oe, respectively (the optimum parameter set that yields the lowest $\varepsilon_{\text{crit,appl}}$ of 4200 ppm). Noticeably, there exists an intrinsic energy density barrier ($\Delta E_{\text{barrier}} = 15709.6$ J/m³) for the vortex-to-buckle switching, which is overcome through the reduction of the elastic energy $\Delta E_{\text{elastic}} = 19970.0$ J/m³. Spatial distributions of f_{stray} , f_{exch} , f_{EB} and f_{elastic} for the initial CW vortex (Figure 4(b)) are shown in Figure 4(c-f), while those for the equilibrium buckle-like domain (Figure 4(g)) are shown in Figure 4(h-k). These spatially variant energy

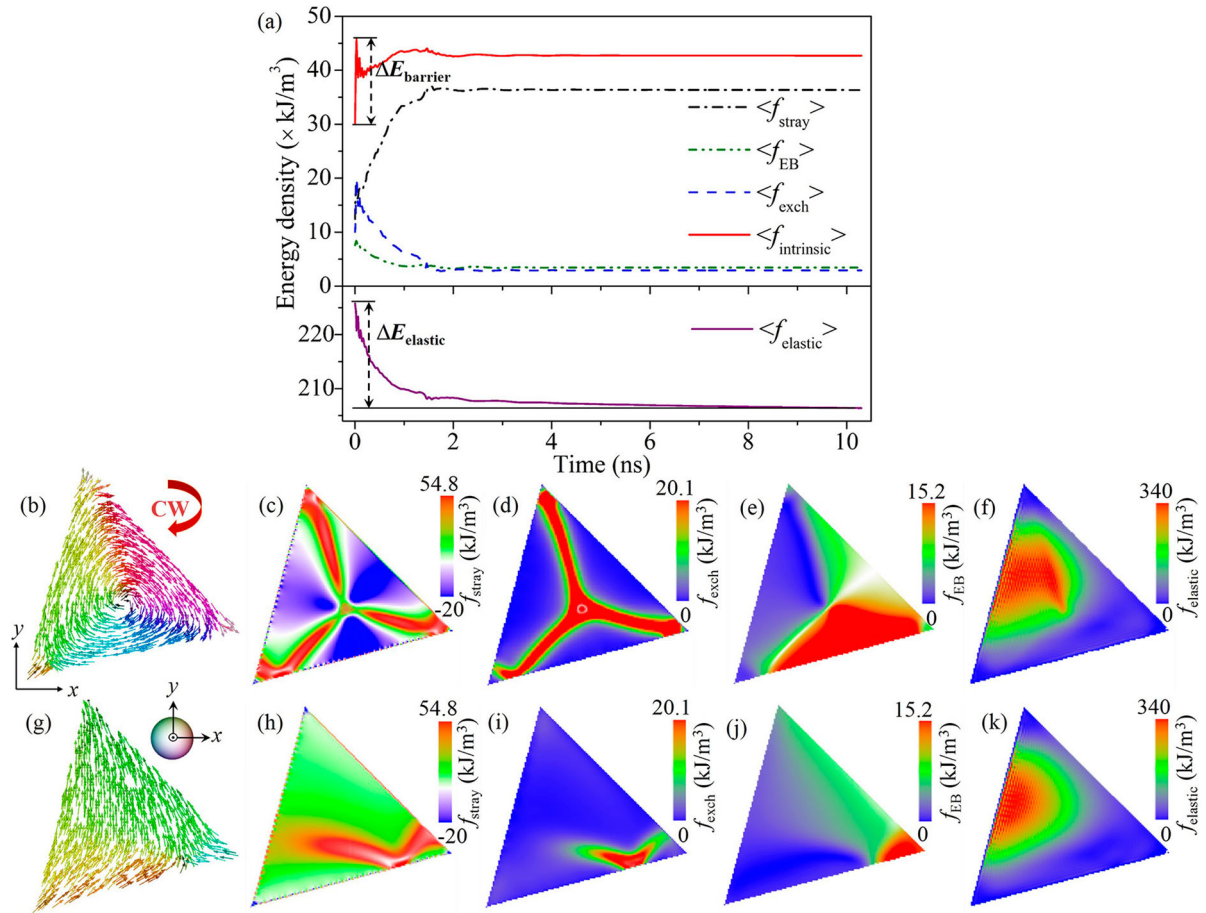


Figure 4. (a) Temporal evolution of different average energy densities when an initial CW vortex is switched to a buckle-like domain under $\varepsilon_{yy} = 4300$ ppm. The bracket indicates the volumetric average. The average intrinsic energy density $\langle f_{\text{intrinsic}} \rangle$ is the sum of $\langle f_{\text{stray}} \rangle$, $\langle f_{\text{exch}} \rangle$, and $\langle f_{\text{EB}} \rangle$. $\Delta E_{\text{barrier}}$ denotes the potential barrier for the switching, overcome by the reduction of $\langle f_{\text{elastic}} \rangle$. (b) Vector diagrams of the initial CW vortex, and (c)–(f) the corresponding spatial distributions of f_{stray} , f_{exch} , f_{EB} , and f_{elastic} in the presence of ε_{yy} , and so forth for the equilibrium buckle-like domain (g–k).

density distributions, along with their volumetric average in Figure 4(a), suggest that the vortex-to-buckle switching is driven by the minimization of f_{exch} , f_{EB} , and f_{elastic} , at the expense of increasing the f_{stray} .

4. Conclusion

In summary, a deterministic and reversible magnetic vortex chirality switching has been computationally demonstrated in an amorphous Terfenol-D triangular nanomagnet purely by applying electric-field-induced bipolar strain pulses. We have shown that the chirality switching includes two processes: (i) the expulsion of vortex core out of the magnet and the formation of a buckle-like domain driven by the co-action of H_{EB} and strain-related uniaxial magnetoelastic anisotropy, and (ii) the nucleation of a new vortex with an opposite chirality after the strain removal. The simulations also indicate that vortex chirality switching can be achieved using

strain pulse whose duration can be as short as about 5 nanoseconds. These findings thus suggest an opportunity of designing an electric-field-controlled vortex-based spintronic device that is fast and has negligible heat dissipation.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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