Creation of Skyrmions by Electric Field on Chiral-Lattice Magnetic Insulators

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It is theoretically proposed that magnetic skyrmions, nanometric spin vortices characterized by a quantized topological number, can be electrically created on a thin-film specimen of chiral-lattice magnetic insulator within a few nanoseconds by applying an electric field via an electrode tip taking advantage of coupling between noncollinear skyrmion spins and electric polarizations. This finding paves the way for utilizing multiferroic skyrmions as information carriers for low-energy-consuming magnetic storage devices without Joule-heating energy losses.

1. Introduction

Skyrmion was theoretically proposed by Tony Skyrme in 1962 as a topological soliton solution for the nonlinear sigma model to account for the stability of baryons in the particle physics. Nowadays, skyrmions are attracting revived research interest in the community of condensed-matter physics. This revival started with theoretical predictions and experimental observations of skyrmions as vortex-like topological spin textures in ferromagnets with chiral crystal symmetry.

In the chiral-lattice ferromagnets, Dzyaloshinskii–Moriya interactions (DMIs) become active, due to the broken spatial inversion symmetry, and favor a rotating spin alignment, while ferromagnetic-exchange interactions favor a parallel spin alignment. It was theoretically predicted that keen competition between these two interactions under a static magnetic field results in the formation of skyrmions as swirling spin textures and skyrmion crystals as triangular arrays of skyrmions. The skyrmion crystal was indeed observed in metallic chiral magnets with B20-type crystal structure such as MnSi, FeGe, and Mn1−xFexGe13 via small-angle neutron-scattering experiments and Lorentz transmission electron microscopies.

Subsequent intensive researches have revealed that magnetic skyrmions possess advantageous properties for application to high-density and low-energy-consuming storage devices, that is, (1) nanometric small size, (2) topological stability, (3) high transition temperatures, and (4) ultralow energy consumption to drive their motion. It was found that translational motion and subsequent Hall motion of skyrmions can be driven in metallic systems by applying spin-polarized electric currents via the spin transfer torque mechanism.16–18 Surprisingly its threshold current density jc turned out to be 105–106 A m−2, which is five or six orders of magnitude smaller than jc required to move magnetic domain walls.

The B20 compounds had been only example of chiral-lattice magnets realizing skyrmionic phases so far, and all of these compounds are metallic. The initial discovery of an insulating skyrmionic phase was reported in 2012 for Cu2OSeO3.19 What’s interesting here is that the noncollinear skyrmion spin structure in the insulator attains multiferroic nature via relativistic spin–orbit coupling. Indeed, magnetically induced ferroelectric polarization was observed in this compound.19–21 This multiferroicity offers an opportunity to manipulate skyrmions by electric fields,22,23 rather than electric currents24–30 or heat pulses.31 Because electric fields in insulators do not bring about energy losses due to the Joule heating in contrast to electric currents in metals, there is a chance to further reduce the energy consumption in potential skyrmion-based storage devices.

To use multiferroic skyrmions as information carriers, it is necessary to establish a method to create, erase, and drive them by applying an electric field. In this paper, by taking Cu2OSeO3 as an example of skyrmion-hosting multiferroics, we theoretically demonstrate that skyrmions can be created on a thin-film sample very quickly (within a few nanoseconds) by applying electric fields with an electrode tip. This electric activity of skyrmions turns out to be mediated by magnetoelastic coupling between the swirling skyrmion spins and the electric polarizations in multiferroics, which is distinct in microscopic mechanism from the spin transfer torque as a major channel of electric control of magnetism in metallic magnets. Therefore this finding will lead to a unique technique for using multiferroic skyrmions for future skyrmion-based memory devices.

2. Model and Simulations

The crystal and magnetic structures of Cu2OSeO3 are composed of tetrahedra with four Cu2+ (S = 1/2) ions as shown in Figure 1a,b, and three-up and one-down-type collinear spin arrangement is realized on each tetrahedron below Tc = 58 K.32,33 This four-spin assembly as a magnetic unit can be treated as a classical...
The magnetic structure of Cu$_2$OSeO$_3$ is described by a classical Heisenberg model using numerical simulations. A static magnetic field is applied within a circular area with diameter of 2 nm sites perpendicular to the plane. We use $J = 3$ meV and $D/J = 0.09$ to reproduce the magnetic transition temperature ($\approx 60$ K) for bulk samples of Cu$_2$OSeO$_3$ and the skyrmion size ($\approx 50$ nm) observed in a thin-plate specimen.

The phase diagram of this model at $T = 0$ is shown in Figure 1c. The skyrmion crystal phase emerges in the range $1.875 \times 10^{-3} < |g \mu_B \mu_H|/J < 6.3 \times 10^{-3}$, sandwiched by the helical and the ferromagnetic phases in agreement with experiments for a thin-plate sample of Cu$_2$OSeO$_3$.[19] Note that the ferromagnetic order of $m_i$ corresponds to the ferrimagnetic order in real Cu$_2$OSeO$_3$ material because $m_i$ represents the ferrimagnetic three-up and one-down spin assembly. In the skyrmion-crystal phase, skyrmions are crystallized into a hexagonal lattice as shown in Figure 1d.[19, 38] In which the magnetizations $m_i$ point parallel (antiparallel) to $H$ at the periphery (center) of each skyrmion. The phase transition between the skyrmion-crystal and ferromagnetic phases is of the strong first order, and thus skyrmions appear not only as a crystallized form but also as topological defects in the ferromagnetic phase. In the following, we demonstrate that isolated skyrmions can be created by locally applying an electric field with an electrode tip on a thin-film specimen in the ferromagnetic phase as shown in Figure 1e.

It was experimentally confirmed that the magnetizations in the noncollinear skyrmion structure induce electric polarizations $p_i$ via the spin-dependent metal-ligand hybridization mechanism.[20] Because of the cubic crystal symmetry, the local polarization $p_i$ in the units of Cm$^{-2}$ from the $i$th tetrahedron is given using the magnetization components $m_{i \alpha}$, $m_{i \beta}$, and $m_{i \gamma}$ in the units of m$^{-1}$ in the cubic setting as

$$p_i = (p_{i \alpha}, p_{i \beta}, p_{i \gamma}) = \lambda (m_{i \alpha} m_{i \beta} m_{i \gamma} m_{i \alpha} m_{i \beta} m_{i \gamma})$$  

(2)
of electric dipole–dipole interactions never affects the electric-polarization distribution, indicating negligible roles of depolarization fields even in thin-film samples. This is because the electric polarization is a subsequent order parameter in this multiferroic system, which is governed by the predominant skyrmion magnetic order determined by strong magnetic interactions such as the ferromagnetic-exchange and the DMIs.

The net magnetization $M$ and the ferromagnetic polarization $P$ are given by sums of the local contributions as $M = (g_{\mu_B}/NV)\sum_{i} m_{i}$ and $P = (1/NV)\sum_{i} p_{i}$, respectively. Here the index $i$ runs over the Cu-ion tetrahedra with three-up and one-down spin pair, $N$ is the number of tetrahedra, and $V = (1.76 \times 10^{-28} \text{ m}^3)$ is a volume per tetrahedron.

The coupling between magnetism and electricity offers an opportunity to create and manipulate magnetic skyrmions electrically through modulating the distribution of electric polarizations. To see this, we numerically simulate dynamics of magnetizations $m_i$ and polarizations $p_i$ under a locally applied electric field by solving the Landau–Lifshitz–Gilbert equation using the fourth-order Runge–Kutta method. The equation is given by

$$\frac{d m_i}{d t} = -m_i \times H^{\text{eff}} + \alpha_C m_i \times \frac{d m_i}{d t}$$  \hspace{1cm} (3)

where $\alpha_C (=0.04)$ is the Gilbert-damping coefficient. The effective field $H^{\text{eff}}$ is calculated from the Hamiltonian $\mathcal{H} = \mathcal{H}_0 + \mathcal{H}'(t)$ as $H^{\text{eff}} = -\partial\mathcal{H}/\partial m_i$. Here the first term $\mathcal{H}_0$ is the model Hamiltonian given by Equation (1), while the term $\mathcal{H}'(t)$ represents the coupling between local polarizations $p_i$ and a DC electric field $E$. The term $\mathcal{H}'(t)$ is given by

$$\mathcal{H}'(t) = -E(t) \sum_{i} p_i$$  \hspace{1cm} (4)

where the electric field $E(t) = (0,0,E_z)$ is applied for a fixed time to the sites within a circular area $C$ with diameter of $2r = 40$ sites. Here, we model the local $E$-field application as a constant $E_z$ within the area but $E_z = 0$ otherwise. The calculations are performed using a system of $N = 320 \times 320$ sites with an open boundary condition.

### 3. Results

Our simulation demonstrates that isolated skyrmions can be created in the field-polarized ferromagnetic state under $H \parallel [111]$. Simulated dynamics of $m_i$ and $p_i$ during the creation process are summarized in Figure 2a–l for $g_{\mu_B} \mu_B H_z / J = 6.3 \times 10^{-3}$ and $E_z = -1.2 \times 10^{-5} \text{ V m}^{-1}$. Relevant areas of $100 \times 100$ sites are magnified in these figures. Note that although the value of $E_z$ is quite large, resulting effective magnetic fields due to the magnetoelectric coupling acting on $m_i$ are not so large because of the small coupling constant $\lambda$, which allows us to neglect amplitude fluctuations of $m_i$ in the simulation.

The application of $E$ with negative $E_z$ induces reorientation of the polarizations $p_i$ in the field-applied area from $p_x > 0$ to $p_x < 0$ as seen in Figure 2a–c. Accompanied by this $p$-reorientation, most of the magnetizations $m_i$ in the area rotate from the out-of-plane direction to the in-plane direction as seen in Figure 2e–g and in Figure 2i–k. We find that a sudden 180° flip of local $m_i$ occurs at the center of the field-applied area between Figure 2f and Figure 2g and between Figure 2j and Figure 2k. Shown in Figure 2m–o are the snapshots of the spatial distribution of energy associated with the DMI. Importantly, the energy becomes significantly high right before the $m_i$ flip at a local site and then suddenly becomes significantly low right after the $m_i$ flip as exemplified by sharp positive and negative peaks in Figure 2m,n, respectively. Once the local $m_i$ flip occurs, a skyrmion structure emerges after switching off the $E$ field through relaxation of the spatial distributions of $m_i$, $p_i$ and the local Dzyaloshinskii–Moriya energy as shown in Figure 2d,h,l,o. The whole process of

![Figure 2.](image-url)
Figure 3. a–e Schematics of the dynamical process of the electric-field-induced skyrmion formation, which focus on alignments of m_i and p_i in a diameter direction of the area onto which a DC electric field is applied.

This skyrmion creation occurs very rapidly only within a few nanoseconds.

In order to understand the mechanism of this electrical creation of skyrmion, the following two facts should be noted. First, the local m_i with dominant out-of-plane (in-plane) component or m_i || [111] (m_i ⊥ [111]) gives rise to local p_i with p_z < 0 (p_z > 0) under H || [111] as seen in comparison between Figure 1f and Figure 1g. Second, the DMI in the model (1) with a positive parameter D > 0 favors a clockwise rotation of m_i propagating in a positive direction indicated by a solid arrow in Figure 3a.

Shown in Figure 3a–e are the schematics of the spatiotemporal dynamics of m_i and p_i aligned along a diameter of the electric-field area. In the initial ferromagnetic state with all the m_i, being parallel to H || [111], all the p_i are uniformly pointing in the [111] direction with p_z > 0 (Figure 3a). When the E-field with E_z < 0 is applied, the magnetizations m_i begin to rotate toward the in-plane direction so as to flop the p_i from p_z > 0 to p_z < 0 because E_z < 0 favors p_z < 0 (Figure 3b). This rotation of m_i occurs in a clockwise fashion near the periphery of the electric-field area so as to smoothly connect the spatial variation of m_i to the outside ferromagnetic region in the presence of DMI. In this situation, the rotation sense around the center of the electric-field area inevitably becomes counterclockwise, which is unfavorable with respect to DMI. When the area of p_z < 0 with in-plane m_i, spreads under E_z < 0, the m_i around the center starts to rotate very abruptly in the counterclockwise fashion (Figure 3c), which causes significantly high energy cost of the DMI as seen in the sharp positive peak in Figure 2m. To solve this energetically unstable alignment of m_i, the m_i at the center eventually floats from m_z > 0 to m_z < 0 (Figure 3d). This local m_i flop realizes an abrupt clockwise rotation of m_i at the center with a large energy gain from the DMI seen as a sharp negative peak in Figure 2n. This locally inverted m_i becomes a skyrmion core. After switching off the E-field (Figure 3d), the alignment of m_i, relaxes to form a skyrmion spin texture shown in Figure 2l–o.

Here, we argue some issues on the initial process of skyrmion creation. First, the signatures shown in Figure 2a,e are not circular because the initial process is governed by a nucleation. A place at which the m_i begins to rotate is accidentally determined by fluctuations of m_i or imperfectness of skyrmion vortex structures in real experimental situations. This effect is incorporated via discreetness of the magnetization distribution or rounding errors in the numerical simulation. Second, the rotation of m_i under the E-field first starts at peripheries, whereas the m_i at the center of the E-field spot remains to point in the [111] direction. This is because the clockwise and counterclockwise rotations of m_i at the center surrounded by ferromagnetic background are degenerate so that it cannot start to rotate. On the other hand, at the peripheries of the E-field spot, this degeneracy is lifted by asymmetry between inside and outside of the E-field area as well as the DMI. There, the m_i can start to rotate in a direction favored by the DMI. Third, although the numerical simulations are performed for a purely 2D model, the skyrmion-creation process and the physical mechanism argued here are expected to survive even for film- or plate-shaped samples with finite thickness. There, the reversal of local m_i should occur first at the top layer, and subsequently the m_i-reversed area expands in the thickness direction to form a tube-shaped skyrmion.

We also discuss the E-field strength required for creating a skyrmion. Although efforts to search for new materials hosting multiferroic skyrmions with larger electric polarizations or stronger magnetoelectric coupling should be unerringly made, it is useful to establish a method to reduce the threshold field for technical application. One promising way is to utilize a sample edge. To create a topological skyrmion texture deep inside a sample, one needs to flop the local m_i with a large energy cost. However, the m_i flop can be achieved with a much smaller energy at the sample edge. This is not only because the number of surrounding spins at the edge is small but also because discontinuity of the magnetization distribution at the sample edge allows continuous change of the topological invariant and relaxes the constraint of topological protection.

In Figure 4a, the number of created skyrmions (0 or 1) is plotted as a function of E_z for different locations of the electric-field area indicated by circles in the insets. When the E-field is applied deep inside the sample (Case 1), the threshold field takes a negatively large value of \(-1.2 \times 10^9\) V m\(^{-1}\). On the other
off. Note that typical threshold $E \approx 100 \text{ MV m}^{-1}$ down is $\times 160$ sites with an open boundary condition. performed for a system of $160 \times 160$ sites with an electrode tip. The applied $E$ field induces twisting of the magnetization alignment and eventually a $180^\circ$ flop of the local magnetization through modulating the spatial distribution of DMI energy as well as the local polarization orientation via magnetoelectric coupling. The skyrmion spin structure grows around the flopped magnetization after switching off the $E$ field. It was found that the required strength of $E$ field can be significantly reduced by applying the $E$ field onto the sample edge where the discontinuity of spatial $m$ distribution at the sample edge relaxes the constraint from the topological protection. Recently, several theoretical proposals on how to drive skyrmions in insulators have been made, and experimental techniques to write skyrmions by a tip with spin-polarized electric currents have been developed. Under these circumstances, control and creation of multiferroic skyrmions by electric fields promise to become an important technique toward spintronics application to realize low-energy-consuming storage devices.

### 4. Summary and Discussion

In summary, we have theoretically demonstrated that skyrmion spin textures can be electrically created on a thin-film specimen of chiral-lattice insulating magnet Cu$_2$OSeO$_3$ within a few nanoseconds by applying a DC electric field $E$ with an electrode tip. The applied $E$ field significantly reduces the threshold electric field to $\sim 4.2 \times 10^8 \text{ V m}^{-1}$. Snapshots of the dynamical $m$ configuration for Case 2 are shown in Figure 4c–f, in which the $m$ flip occurs at the sample edge. However, if the electric-field area is too close to the sample edge (Case 3), skyrmions cannot be created. More concretely although the local flop of $m$ occurs at the edge with much lower energy in Case 3, the seed of skyrmion is absorbed by the edge and vanishes immediately after the $E$ field is turned off. Note that typical threshold $E$ field for the dielectric breakdown is $\sim 100 \text{ MV m}^{-1}$ if the $E$ field is applied to bulk of the sample with a plate electrode, but the dielectric breakdown does not occur even with a stronger field of $1$–$10 \text{ GV m}^{-1}$ if the $E$ field is applied only locally with an electrode tip.

Another way to reduce the threshold field is tuning the external magnetic field $H_z$. The phase transition from the ferromagnetic phase to the skyrmion-crystal phase is of strong first order. As a result, the ferromagnetic phase remains as a metastable state even below the critical magnetic field. Figure 4 shows $E_z$-dependence of the skyrmion creation for several values of $H_z$. We find that the threshold electric field is reduced as $H_z$ is decreased.

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