Nematic and smectic stripe phases and stripe-SkX transformations

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Received October 23, 2021; accepted January 7, 2022; published online March 3, 2022

Based on the findings of skyrmion nature of stripes and the metastability of a state of an arbitrary number of skyrmions, precisely controlled manipulation of stripes of skyrmion number 1 in pre-designed structures and mutual transformation between helical states and skyrmion crystals (SkXs) are demonstrated in chiral magnetic films. As a proof of the concept, we show how to use patterned magnetic fields and spin-transfer torques (STTs) to generate nematic and smectic stripe phases, as well as “UST” mosaic from three curved stripes. Cutting one stripe into many pieces and coalescing several skyrmions into one by various external fields are good ways to transform helical states and SkXs from each other.

spinitronic, Landau-Lifshitz-Gilbert equation simulation, stripe skyrmion, skyrmion crystal, nematic phase

PACS number(s): 75.50.Gg, 75.70.Ak, 75.60.Ch

Citation: H. T. Wu, X.-C. Hu, and X. R. Wang, Nematic and smectic stripe phases and stripe-SkX transformations, Sci. China Phys. Mech. Astron. 65, 247512 (2022), https://doi.org/10.1007/s11433-021-1852-8

1 Introduction

Magnetic skyrmions, topologically non-trivial spin textures characterized by skyrmion number \( Q = \frac{1}{4\pi} \int \mathbf{m} \cdot (\partial \mathbf{m} \times \partial_x \mathbf{m}) \, dx \, dy \), provide a fertile ground for studying fundamental physics such as the topological Hall effect that is a phenomenon about how non-collinear spins in skyrmion crystals (SkXs) affect electron transport [1-3]. Here \( \mathbf{m} \) is the unit vector of the magnetization. Skyrmions were observed in systems involving Dzyaloshinskii-Moriya interaction (DMI) [4-9] or geometric frustration [10-12]. Skyrmions are commonly believed to be circular objects, and three families of circular skyrmions have been identified, namely spiral (Bloch type) skyrmions, hedgehog (Néel type) skyrmions, and anti-skyrmions [1,4,8,9]. Recently, it is shown that irregular stripes and maze structures are also skyrmions with topological skyrmion number 1 [13]. With this expanded zoo, skyrmions provide a useful platform for studying fundamental sciences, other than potential applications in information technology. For example, one can study the interplay of topology, shape, spin, and charge. One can ask how topologically non-trivial textures in various forms affect electron transport if a precise control of condensed skyrmion states is possible? Creation and control of topologically non-trivial stripes in long-term searching [1] nematic and smectic phases with pre-designed elongation and orientation are the main theme of the current study.

Many efforts have been made in skyrmion generations, manipulations, and detections [3,7,14-48]. Magnetic fields [14-22], electric fields [21,23-34], currents [3,7,35-40], ge-

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ometric constrains [41–43], spin waves [44–46], and temperature gradient [16, 17] have been used to generate and manipulate skyrmions. There were also demonstrations of how to use STM to add and delete a skyrmion in SkXs [7]. With all the advances made to date in skyrmion manipulation, the control of helical states and SkXs often relies on the luck and a hunch. It is a formidable task to control the shape and morphology of individual stripes and the overall arrangement of a group of them. This is why the long-time suspected liquid-crystal-like skyrmion phases such as nematic or smectic configurations have not been found yet [1]. It is also not clear how to precisely control transitions from helical states to SkXs. The lack of the ability in stripe control is largely due to our ignorance about the skyrmionic nature of stripes and the origin of complicated stripe morphologies that include dendrite-like and maze structures. Our recent discovery of the skyrmion nature of stripes and sensitivity of stripe morphology to skyrmion number density [13, 49] provides new thoughts about stripe-state-control and possible control of transformations between helical states to SkXs at nanometer scale.

In this paper, how to use patterned spin-transfer torques (STTs) to create a long-term searching nematic and smectic stripe phase is demonstrated. The lengths and orientations of stripes can be controlled by the skyrmion density and arrangement using patterned fields and STTs. Each stripe has a skyrmion number 1. The smectic stripe phase becomes an SkX when the stripe length is comparable to the stripe width. It is also possible to transform an SkX to a nematic or a smectic phase by using field pulses to coalesce skyrmions. It is even possible to construct a symbol of “UST” with three curved topologically non-trivial stripes.

2 Model and methods

We consider a thin chiral magnetic film of thickness $d$ in the $xy$-plane. Its magnetic energy reads

$$E = d \int \left[ \langle \mathcal{A} \mathcal{V} m \rangle^2 + D \mathcal{V} \mathcal{V} \mathcal{V} \mathcal{V} m \cdot m - (\mathcal{V} m \cdot m) \mathcal{V} m \rangle \right] + K_e (1 - m^2_\parallel) - \mu_0 M_s (H + H_0) \cdot m \, dS,$$

(1)

where $A$, $D$, $K_e$, $\mu_0$, $M_s$, $H$, and $H_0$ are the Heisenberg exchange stiffness, the DMI coefficient, the perpendicular magneto-crystalline anisotropy, the vacuum permeability, the saturation magnetization, the external magnetic field, and the dipolar field, respectively. $E = 0$ is chosen for state of $m = \hat{z}$. In the analytical calculations, the static magnetic interaction for a thin film can be included through the effective magnetic anisotropy constant $K = K_e - \mu_0 M_s^2 / 2$ (dipolar interaction is fully included in all of our MuMax3 simulations [50]).

This theoretical approximation is good when the film thickness $d$ is much smaller than the exchange length $[51, 52]$. Magnetization unit vector $m$ is governed by the Landau-Lifshitz-Gilbert (LLG) equation:

$$\frac{d m}{dt} = -\gamma m \times \mathbf{H}_{\text{eff}} + \alpha m \times \frac{d m}{dt} + \tau,$$

(2)

where $\gamma$ and $\alpha$ are the gyromagnetic ratio and the Gilbert damping constant, respectively. $\mathbf{H}_{\text{eff}} = \frac{2A}{\mu_0} \mathcal{V} \mathcal{V} \mathcal{V} \mathcal{V} m - \frac{2K_e}{\mu_0} M_s \hat{z} + \mathbf{H}_{\text{DMI}} + \mathbf{H}_0$ is the effective field including the exchange field, the magneto-crystalline anisotropy field, the DMI field $\mathbf{H}_{\text{DMI}}$, the external magnetic field $H$, and the magnetic dipolar field $H_d$. $\tau = \alpha m \times (\mathbf{m}_p \times m) - \beta m \times \mathbf{m}_p$ is STTs due to spin polarized electric current or spin current of polarization $\mathbf{m}_p$ [53], where $a$ proportional to charge current density $J$ describes out-of-plane torque, and $\beta$ is a dimensionless parameter characterizing the in-plane torque. In this study, $\mathbf{m}_p = \hat{z}$ is assumed if not stated otherwise. Eq. (2) is numerically solved by MuMax3 package [50] for various patterned currents and magnetic fields. It should be pointed out that MuMax3 [50] includes properly the demagnetization field and considers both open or periodic boundary conditions. The results in this work are for the open boundary conditions (see Supporting Information). Mesh size in this study is $3 \, \text{nm} \times 3 \, \text{nm} \times 1 \, \text{nm}$. A large $\alpha = 0.3$ is used to speed up stable spin structure search. $\alpha$ does not affect the properties of stable and metastable states. Skyrmion number of a given spin texture is calculated according to its definition, which can be extracted directly from MuMax3 [50]. The material parameters are $A = 0.41 \, \text{pJ} \, \text{m}^{-1}$, $K_e = 30 \, \text{kJ} \, \text{m}^{-3}$ ($K = 4.9 \, \text{kJ} \, \text{m}^{-3}$), $D = 0.12 \, \text{mJ} \, \text{m}^{-2}$, and $M_s = 0.2 \, \text{MA} \, \text{m}^{-1}$ (see Supporting Information), unless otherwise stated.

3 Principles of stripe-state-control

One of the breakthroughs in skyrmion physics is the understanding of skyrmion nature of all kinds of stripes, long and short, curved and straight, ramified and non-ramified, in helical, spiral, conical states and in dendrite-like and maze structures. Stripes are the natural form of skyrmions when $\kappa \equiv \pi^2 D^2 / (16AK) \gg 1$, and the ground state is a condensed skyrmion phase with skyrmions occupying the whole chiral magnetic film, in contrast to isolated circular skyrmions that are metastable in a film with $\kappa \equiv \pi^2 D^2 / (16AK) < 1$ [13, 51]. The film with an arbitrary number of skyrmions is metastable [13, 49]. This is very similar to a BEC condensate with many atoms staying together (in one energy state). These stripes, attempting to fill up the whole system, have a well-defined width of $L = f(x) A / D$ with $f(x) = 2 \pi$ for $x \gg 1$ [13, 49]. These new understandings are supported by the observation of topological charges in stripe structures [54, 55].
and continuous deformation between circular skyrmions and stripes [56-59]. No fundamental difference between these skyrmions of different shapes is a putative conclusion of the new understanding, and transformation from one into another is therefore highly possible if a proper kinetic path is used. The final stripe morphology depends on skyrmion number density, the initial configuration, and the actual spin dynamics. These multiple effects explain the rich morphologies and structures of the condensed skyrmion phases. This new understanding of the condensed skyrmion phases provides a new methodology of creating and manipulating ordered stripe structures by using proper external forces, such as patterned fields and spin torques, to control the initial skyrmion seeds and their locations, as well as spin dynamics.

4 Arbitrary skyrmion structures

As a proof of the concept, a 900 nm × 900 nm × 1 nm chiral magnetic film with parameters given in sect. 2 is considered. This film has \( x > 1 \) such that its stable static states are stripe skyrmions filled the whole sample [13, 49]. It is convenient to use a coordinate system with the origin at the left bottom corner such that the film is in 0 nm ≤ \( x \) ≤ 900 nm, 0 nm ≤ \( y \) ≤ 900 nm. In this study, the initial state is a perpendicular ferromagnetic state of \( m_z = -1 \) with the help of a strong magnetic field of \( \mu_0 H = -100 \text{ mT} \).

At \( t = 0 \), a patterned STT pulse of 10 ns long is used to create different ordered nucleation domains of \( m_z = 1 \) in the ferromagnetic background. The STT increases linearly from 0 to its full value of \( a = 3.45 \times 10^{10} \text{ s}^{-1} \), corresponding to an electric current density of \( 2.0 \times 10^7 \text{ A cm}^{-2} \), in 1 ns and linearly decreases later to zero from \( t = 9 \text{ ns} \) to \( t = 10 \text{ ns} \) as shown in Figure 1(e2). \( \mu_0 H \) is linearly switched off from \( t = 9 \text{ ns} \) to \( t = 10 \text{ ns} \) as shown in Figure 1(e1). Figure 1(a) shows 153 stripes of 30 nm wide and 78 nm long in a stable/metastable smectic phase at \( t = 5 \text{ ns} \) after the STT pulse is applied to 153 rectangular areas of \( (nl_x - 30 \text{ nm}) \leq x \leq nl_x \) (\( ml_y - 83 \text{ nm} \) ≤ \( y \) ≤ \( ml_y \)), \( n = 1, 2, \ldots, 17 \), \( m = 1, 2, \ldots, 9 \) with \( l_x = 52 \text{ nm} \) and \( l_y = 98 \text{ nm} \). The corresponding STT pattern is shown by white rectangles in Figure 1(g1), where an STT torque of \( a = 3.45 \times 10^{10} \text{ s}^{-1} \) is applied. The STT pulse reverses some spins in these areas that evolve into well-aligned stripes. The process is captured by the evolutions of system energy \( E \) and skyrmion number \( Q \) as shown in Figure 1(f1). Under the STT and \( \mu_0 H \), the system quickly reaches the stable smectic phase represented

![Figure 1](image-url) (Color online) Creation of smectic and nematic stripe phases. (a) Stripe skyrmions in a stable smectic phase in the presence of a magnetic field (e1) and a patterned STT (e2). (b) Stable/metastable smectic stripe phase after removal of the magnetic field and the STT. Stripes tilt a 24° from the y-direction. (c) Stable/metastable smectic phase of longer stripes after removal of the magnetic field (e1) and the patterned STT (e2). Stripes tilt a 10° from the y-direction. (d) Stable/metastable nematic phase after removal of the magnetic field (e1) and the patterned STT (e2). Color encodes in-plane magnetization for \( m_z > 0 \), the background of \( m_z < 0 \) is in gray. Time dependences of the magnetic field pulse (e1) and the STT pulse (e2). Evolution of total energy \( E \) and topological skyrmion number \( Q \) for 153 (f1) and 100 (f2) ordered nucleation domains, and 80 odd-even columns aligned nucleation domains (f3). (g1)-(g3) show patterned STTs that produce spin textures (b), (c), and (d), respectively. STT torque of \( a = 3.45 \times 10^{10} \text{ s}^{-1} \) is applied in the white areas.
by constant $Q$ and $E$. Figure 1(b) is the stable smectic stripe phase at $t = 15$ ns in the absence of the magnetic field and the STT. Stripes tilt an angle of $24^\circ$ from the $\hat{y}$-axis (the Inset). The whole process from Figure 1(a) to (b) is captured in the first part of Video 1 (see Supporting Information). A smectic phase can also be obtained in a bulk sample by the same method where each stripe is replaced by a stripe tube that can be viewed as stacked stripes, similar to the skyrmion strings in the literature (see Supporting Information).

The length of stripes can be controlled by varying the length of rectangles where STT is applied. Figure 1(c) is the final stable/metastable smectic stripe phase in the absence of the field and the STT, after the STT pulse of Figure 1(e2) is applied on 100 rectangular areas of $(m_i \leq 36 \text{ nm}) \leq x \leq (m_i - 12 \text{ nm})$, $(m_i - 166 \text{ nm}) \leq y \leq (m_i - 12 \text{ nm})$, $n = 1, \ldots, 20$, $m = 1, 2, \ldots, 5$ with $l_x = 45$ nm and $l_y = 180$ nm. Stripe skyrmions are 162 nm long, longer than those in Figure 1(a) and (b). The corresponding STT pattern is shown in Figure 1(g2). Stripes are inclined away from the vertical direction for very simple physics: the stripe width $L$ is fixed [13,51] while their length is stretchable in order to lower their energy due to the negative formation energy of skyrmions. For $N$ parallel aligned stripes of along $L_x$, stripes will incline away from the vertical direction if $L_x > 2NL$. The tilted angle $\Theta$ satisfies $2L/(\cos \Theta) = L_x/N$. For stripes in Figure 1(b), $N = 17$, $L_x = 900 \text{ nm}$, $L = 23 \text{ nm}$ such that $\theta = \cos^{-1}(46/53) \approx 28^\circ$. For stripes in Figure 1(c), $N = 20$, $L_x = 900 \text{ nm}$, $L = 22 \text{ nm}$ such that $\theta = \cos^{-1}(44/45) \approx 12^\circ$, which are very close to the observed values.

In order to create a nematic phase with 80 stripes, we apply a field pulse of Figure 1(e1) and a patterned STT pulse of Figure 1(e2) on 80 rectangular areas: $(m_i \leq 36 \text{ nm}) \leq x \leq (m_i - 12 \text{ nm})$, $18 \text{ nm} \leq y \leq 114 \text{ nm}$ or $(m_i - 126 \text{ nm}) \leq y \leq (m_i + 111 \text{ nm})$ for odd $n$, and 792 nm $\leq y \leq 885 \text{ nm}$ or $(m_i - 240 \text{ nm}) \leq y \leq m_i$ for even $n$, $n = 1, \ldots, 20$, $m = 1, 2, 3, 4, 5, \ldots, 80$. $l_x = 45$ nm and $l_y = 258$ nm. A stable nematic stripe phase is obtained in the absence of the field and the STT as shown in Figure 1(d). The corresponding STT pattern is shown in Figure 1(g3). Skyrmion number $Q$, as well as stripe number, in two smectic phases (Figure 1(b) and (c)) and the nematic phase (Figure 1(d)) are 153, 100, and 80, respectively. This supports the claim that all stripes have skyrmion number 1. The widths of all stripes in these figures are the same about 22 nm, smaller than the stripe width in the presence of the field and the STT that prefers wider skyrmions as shown in Figure 1(a).

It is also possible to transform one stripe phase into another by using external forces. For example, starting from the stable smectic phase in Figure 1(b) where stripes align $24^\circ$ north-east, stripes shrink into disks as shown in Figure 2(a), 4 ns after a $\mu_0 H_z = -60 \text{ mT}$ field pulse shown in Figure 2(c) is applied at $t = 0$. Each disk is a circular skyrmion of skyrmion number 1 as shown in Figure 2(e) where skyrmion number $Q$ and energy $E$ do not change with time. At $t = 4$ ns, $\mu_0 H_z$ is linearly switched off and an in-plane field pulse of $\mu_0 H_{i} = 54 \text{ mT}$ strong and 12 ns long, pointing $24^\circ$ south-east indicated by the arrow in Figure 2(a), is switched on at the same time. The time dependence of two field pulses are given in Figure 2(c) and (d), respectively. A new stable smectic phase where stripes align $24^\circ$ north-west as shown in Figure 2(b) is obtained after the removal of external fields. The transformation between two smectic phases is recorded in the second part of Video 1 (see Supporting Information).

Since condensed skyrmions prefer an SKX structure when the skyrmion-skyrmion distance is comparable to the stripe width, an SKX can also be obtained from a ferromagnetic state of $m_z = -1$ by creating a denser skyrmion nucleation centers with using the same field and STT pulses described in Figure 1(e1) and (e2). This can be achieved by applying the STT pulses on 340 rectangular areas of $(m_i \leq 30 \text{ nm}) \leq x \leq (m_i - 12 \text{ nm})$, $(m_i - 42 \text{ nm}) \leq y \leq (m_i - 12 \text{ nm})$, $n = 1, 2, \ldots, 17$, $m = 1, 2, \ldots, 20$ with $l_x = 52$ nm and $l_y = 45$ nm. Figure 3(a)

![Figure 2](Color online) Transformation between different stripe smectic phases. (a) Circular skyrmions in a crystal structure at $t = 4$ ns after applying a field of $-60 \text{ mT}$ on the smectic phase of Figure 1(b). (b) The new stable smectic phase at $t = 25$ ns when two series of magnetic field pulses of $\mu_0 H_z$ (c) and $\mu_0 H_i$ (d) are removed. (e) Evolution of total energy $E$ and skyrmion number $Q$. 
shows the stable SkX at \( t = 15 \text{ ns} \) in the absence of both fields and STTs. Inset of Figure 3(a) shows the corresponding STT pattern.

It is even possible to use stripes to create other more exotic patterns like “UST” mosaic, as long as two neighboring stripes have a distance around their natural width. As shown in Figure 3(b), a “UST” mask is designed in a 230 nm \( \times \) 230 nm \( \times \) 1 nm film that has the same material parameters as those in Figures 1 and 2. The film is initially in the ferromagnetic state of \( m_z = -1 \) under the field pulse shown in Figure 1(e1). At \( t = 0 \), the STT pulse of Figure 1(e2) is applied on the mask of Figure 3(b), and Figure 3(c) is the final stable pattern 15 ns after both the magnetic field and the STT are switched off. This process is recorded in Video 2 (see Supporting Information). To substantiate our claim that both SkX and “UST” mosaic are stable spin structures, Figure 3(e1) and (e2) plot the time evolution of energy \( E \) (the red and the left axis) and skyrmion number \( Q \) (the blue and the right axis) for SkX and “UST” mosaic systems. Clearly, both \( E \) and \( Q \) become constants shortly after \( t = 10 \text{ ns} \). Furthermore, it is interesting to notice that “UST” mosaic is made from three stripes, each one of which has skyrmion number 1 and is in shape of “U”, “S”, and “T”, respectively.

Only interfacial DMI is considered so far, but the results are essentially the same in a film with bulk DMI. If the interfacial DMI \( D(m \cdot \nabla \cdot m - (m \cdot \nabla) m) \) in eq. (1) is replaced by the bulk-type DMI of \( \psi_{\text{bulk}} \) (eq. (1)) using exactly the same mask of Figure 3(b) and the same field and STT pulses of Figure 1(e1) and (e2), similar “UST” mosaic is obtained as shown in Figure 3(d). The only difference is that the Neel-type stripes in the interfacial DMI become Bloch-type stripes in a film with bulk DMI [13].

5 Structure transformations

Cutting stripes into smaller pieces is a good way to transform helical states into SkXs. This method is beyond thermodynamic process and can directly drive a system from one metastable state into another one. Using the smectic phase of Figure 1(c) as an example, a field pulse of \(-500 \text{ mT} \) strong and 5 ns long is applied in 8 rectangular areas of \( 0 \leq x \leq 900 \text{ nm} \), \( (m_y - 30 \text{ nm}) \leq y \leq m_y \), \( m = 1, 2, \ldots, 8 \) with \( h_y = 42 \text{ nm} \). The field pulse, whose shape is shown in Figure 4(d), cuts the two lower rows of stripes in Figure 1(c) into 8 evenly spacing smaller pieces that become circular skyrmions and are in a lattice structure. Figure 4(a) shows coexistence of a smectic stripe phase and an SkX at \( t = 15 \text{ ns} \). Figure 4(e1) shows how the energy (the red and the left axis) and the skyrmion number (the blue and the right axis) vary with time after the field pulse.

It is also possible to transfer an SkX into a nematic phase by coalescing many skyrmions into one. As exemplified in the SkX of Figure 3(a), a strong magnetic field along the \( \hat{z} \)-direction can coalesce skyrmions. Figure 4(c) shows the final stable nematic stripe phase after a field pulse of the same shape illustrated in Figure 4(d) (but along the \( \hat{z} \)-direction) is

![Figure 3](image-url)

*Figure 3* (Color online) Creation of an SkX and a “UST” mosaic. (a) A stable SkX in a 900 nm \( \times \) 900 nm \( \times \) 1 nm film at \( t = 5 \text{ ns} \). Inset is the corresponding STT pattern. A STT torque pulse of \( a = 3.45 \times 10^9 \text{ eV}^{-1} \) is applied in the white areas. (b) The well designed mask for producing “UST” mosaic. (c) The stable “UST” mosaic on a 230 nm \( \times \) 230 nm \( \times \) 1 nm film at \( t = 20 \text{ ns} \) after removal of field and STT pulses. (d) “UST” mosaic for the bulk DMI of the same strength as that for (c) at \( t = 20 \text{ ns} \) after removal of the field and the STT. The only difference between (c) and (d) is the Neel-type stripe wall to the Bloch-type. (e1), (e2) Evolution of energy \( E \) and skyrmion number \( Q \) for SkX and “UST” systems, respectively.
applied to a patterned film that consists of 42 rectangles of 18 nm wide and various lengths indicated by the green color in Figure 4(b). The field pulse coalesces circular skyrmions into stripe skyrmions, and transforms an SkX into a nematic stripe phase. As shown in Figure 4(e2), the nematic phase is a stable spin structure of the system since both energy $E$ and skyrmion number $Q$ do not vary with time 10 ns after external stimulus is switched off. The film, starting with more than 300 circular skyrmions before the magnetic field pulse, consists of 42 stripes and a number of disk-like skyrmions after the field pulse.

6 Discussion and conclusion

All structures we obtained are stable/metastable against thermal agitation. To substantiate this assertion, we performed MuMax3 simulations at a finite temperature [50, 60]. Video 3 (see Supporting Information) shows the stability of smectic phase of Figure 1(b) at $T = 5$ K ($T_c$ is around 30 K) in the absence of fields and STTs. Stripe skyrmions keep their shape and arrangements unchanged under thermal agitation (see Supporting Information). Actually, as far as the temperature is not too close to $T_c$, metastable spin textures keep unchanged for a long time [49].

Although only magnetic fields and STTs are used here to generate different spin structures and to induce transformations from one ordered skyrmion structure into another, other external forces, such as spin-orbit torques, are equally good as long as they can induce magnetization reversal such that nucleation domains can be created to generate skyrmions.

One important issue is the feasibility of approaches studied here. Firstly, insulating and superconducting masks of nano-meter scale should not be a problem for today’s technology. In terms of patterned fields or STTs, one may put masks on both sides of the film using either insulating materials or superconducting materials to shield either fields or electric currents such that one can realize the desired STT or field patterns. For example, one can use standard magnetic tunnelling junction (MTJ) with a ferromagnetic fixed layer for STT generation and a chiral magnetic free-layer sandwiching a spacing layer. A patterned STT will be generated if a tunnelling current passes through the structure. It should not be hard to fabricate structures or masks such as the one shown in Figure 5 at nanometer scale with state-of-art photolithography technologies. Also, masks for generating those patterned STTs and fields shown in the Figures 1-4 should be also an easy task with using existing nano-fabrication facilities such as all kinds of lithography technologies, ion beam, and all kinds of etching methods.

Apart from generating the long-term searching nematic/smectic phase, one potential application of our result is neuromorphic computing. Stripes may work as non-volatile synapse encoding the synapse connections by stripe shapes and orientations through the tunnelling magnetoresistance.
Figure 5  (Color online) System illustration: A MTJ with designed electrodes. The lower MTJ is made from a perpendicularly magnetized fixed layer at the bottom and a chiral magnetic free layer on the top (spacing layer is not shown). Various exotic phases are created in the free-layer. A spin polarized charge current after passing through the fixed layer can create a patterned STT in the free layer under the electrodes.

or Hall resistance. One attraction of stripe synapses is the controllability by stimulus, such as fields and spin torques. Stripe-based neuromorphic devices shall be more robust than isolated skyrmions-based devices, because of the higher energy barrier and entanglements.

In summary, how to use patterned magnetic field and STT pulses to create various ordered stripe phases is demonstrated. Based on the stripe nature of skyrmions in the ground state of a chiral magnetic film that can host an arbitrary number of skyrmions, the creation of long-term searching nematic and smectic stripe phases is demonstrated. Cutting long stripes into shorter pieces or coalescing many small skyrmions into one stripe skyrmion is a useful way to transform various stripe structures from each other and into SkXs, and vice versa. It is also demonstrated how to create curved stripes that form a “UST” mosaic. These findings provide a guidance to skyrmion manipulations.

This work was supported by the National Key Research and Development Program of China (Grant Nos. 2018YFB0407600, and 2020YFA0909900), the National Natural Science Foundation of China (Grant Nos. 11974296, and 11774296), and Hong Kong Research Grant Council (Grant Nos. 16301518, and 16301619).

Supporting Information

The supporting information is available online at phys.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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