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ABSTRACT

Magnetic skyrmions are attractive for representing data in next-generation spintronic devices owing to their stability, small size, and ease of manipulation with spin torques. In order to realize such devices, it is necessary to be able to write, manipulate, and read back data by means of nucleating, propagating, and detecting skyrmions using an all-electrical approach. Here, we review the basic concepts underpinning magnetic skyrmions, describe our recent results on their electrical nucleation, propagation, and detection, and offer some perspectives for future research in this vibrant field.

I. INTRODUCTION

Magnetic skyrmions are topologically non-trivial spin textures with particle-like properties. Skyrme originally introduced the idea of a topological soliton as a model of a particle in high-energy physics,[1] but this concept has found utility in many branches of physics including condensed matter.[2] Originally predicted theoretically to be stabilized by the Dzyaloshinkii–Moriya interaction (DMI),[3] skyrmions were first observed at low temperatures in chiral magnetic materials MnSi[4] and $Fe_{0.5}Co_{0.5}Si$[5] and atomic monolayers, in which the DMI is generated at the interface.[6]

Magnetic skyrmions are now routinely observed at room temperature. This can either be in bulk materials in which they are stabilized by a DMI[7] or frustration[8] or in magnetic multilayers that possess interfacial DMIs.[9–12] They are also known to respond to spin-transfer[13,14] and spin–orbit torques[15,16] and so can be electrically manipulated, opening up the prospect of skyrmion-based spintronic devices.

There are several recent reviews that cover different aspects of this very active field,[17–25] as well as a recently published skyrmion roadmap.[26] In this Perspective, we focus on spintronic aspects of skyrmions, especially those in magnetic multilayers with interfacial DMI. After giving some general background to introduce the main concepts, we review our own contributions to the field in the context of the work of others and then conclude by giving our outlook for the future.

II. BACKGROUND

A magnetic skyrmion is a localized spin texture with a form like that shown in Fig. 1. Strictly, it has a point-like core that is oppositely magnetized to the spins around the edge, whose uniform magnetization allows it to be embedded in a uniformly magnetized magnetic material or else form lattices.[4,5] Surrounding the core is a splay or swirl of spins that cover every direction in space. In fact, in thin films, the core is often a small uniformly magnetized region—a circular reversed domain—that is surrounded by a "swirling" domain wall. Such structures are sometimes referred to as skyrmion bubbles in reference to bubble domains, which lack the "swirling" domain wall. Nevertheless, in this Perspective, we shall term all such structure skyrmions since they are topologically equivalent. The form and sign of the DMI enforces the nature and chirality of the domain wall around the core. Usually in bulk DMI materials, the skyrmions have a Bloch structure [Fig. 1(b)], whereas an interfacial DMI leads to a Néel structure [Fig. 1(a)]. Skyrmion diameters range from the nm to the μm scale, although several tens or a few hundred nm are typical. In thin films, the skyrmions do have the disk-like character shown in the figure, while in three-dimensional bulk materials they extend into tubes.[27–29]

The topological nature of the skyrmion is captured mathematically by the winding number S defined as

$$S = -\frac{1}{4\pi}\int \hat{\mathbf{m}}\cdot(\partial_x\hat{\mathbf{m}}\times\partial_y\hat{\mathbf{m}})dxdy, \quad (1)$$

where $\hat{\mathbf{m}}$ is a unit vector in the direction of the local magnetization and the skyrmion occupies the x-y plane. This takes a value of $S=1$ for an object with skyrmion topology, distinct from the value of $S=0$ for a uniformly magnetized or otherwise topologically trivial state. The requirement to make the jump between discrete values of S to create or annihilate a skyrmion in an otherwise uniformly magnetized

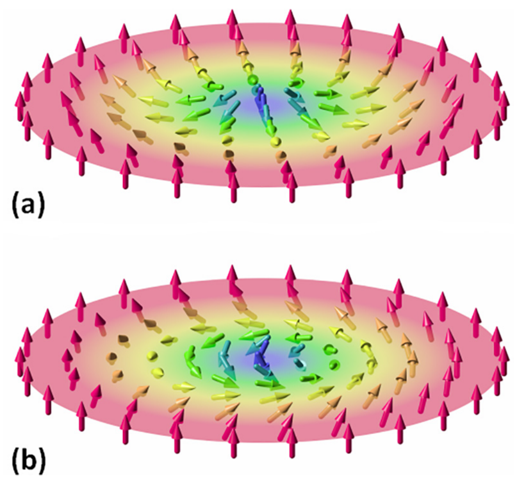

FIG. 1. Spin textures for (a) Néel-type and (b) Bloch-type skyrmions. The core (blue) points in the opposite direction to the edge (red). A spin pointing in every direction in space can be found somewhere within the skyrmion. Reproduced with permission from K. Everschor-Sitte and M. Sitte, see https://creativecommons.org/licenses/by-sa/3.0 for CC BY-SA 3.0, via Wikimedia Commons. Copyright 2015 Authors, licensed under a CC-BY License.[30]

material provides a weak form of topological protection to skyrmions, enhancing their stability. It is not possible to smoothly deform one state into the other. A geometric interpretation of S is the number of times a sphere in spin space is completely wrapped by the spin texture in question. A good recent discussion of the various forms of topological protection for different types of skyrmion materials can be found in Ref. 31.

The winding number also represents the topological charge of the spin texture, which takes discrete integer values. As electrons pass through spin textures, they acquire a Berry phase,[32] which will, as a result, be quantized. This Berry phase can be viewed as giving rise to an emergent magnetic flux acting on the electrons,[33] which turns out to be quantized in units of the flux quantum, $\Phi_0 = h/e$. In a skyrmion lattice with unit cell of area A, we can then write the emergent flux density as $B_e = S\Phi_0/A$. It is important to note that while this emergent flux density is a mathematical concept necessary to take account of the Berry phase, it, nevertheless, exerts a Lorentz force on the conduction electrons. This force then gives rise to a contribution to the transverse resistivity known as the topological Hall effect,[34,35] which can be written as $\rho_{xy} = R_H P B_e$, where R_H is the ordinary Hall coefficient and P is the spin polarization of the current. Hall signals of this sort have been used as evidence for the presence of a skyrmion lattice in MnSi.[36–38] A further aspect to this emergent electrodynamics is that once the skyrmions are set in motion, such as by a spin-torque exerted by the current, an emergent electric field is generated that is given in analogy to Faraday's law of induction by $\mathbf{E}_e = -\mathbf{v}_d \times \mathbf{B}_e$, where $\mathbf{v}_d$ is the drift velocity of the skyrmions. This provides a Hall voltage opposite in sign to that generated by the topological Hall effect and will completely cancel it once the skyrmions are drifting at the same velocity as the current-carrying electrons.[39]

Since skyrmions are rigid particle-like objects, their dynamics is amenable to modeling using a modified form of the Thiele equation,[17,33] which for spin–orbit torques can be written as[40]

$$\mathbf{G} \times \mathbf{v}_d + \alpha \mathscr{D} \times \mathbf{v}_d + 4\pi \mathscr{B} \cdot \mathbf{J}_{hm} = 0, \tag{2}$$

where $\mathbf{G} = (0, 0, -4\pi S)$ is the gyromagnetic coupling vector that is directly coupled to the presence of topological charges. In the dissipation term, α is the Gilbert damping coefficient and $\mathscr{D}$ is a dissipative force tensor, while in the spin–orbit torque term, $\mathscr{B}$ is a tensor that quantifies the efficiency of the spin–orbit torque over the skyrmion texture, while $\mathbf{J}_{hm} = \mathbf{J}_s/\theta_{sh}$ is the electrical current density flowing in the heavy metal that provides the spin–orbit torque by means of the spin Hall effect with spin Hall angle θ_{sh} leading to a spin current density $\mathbf{J}_s$. The presence of a gyrovector with finite value means that a skyrmion experiences a transverse Magnus force in addition to a driving force along the current direction, leading to motion at an angle to the driving force. This phenomenon is known as the skyrmion Hall effect and is quantified by the spin Hall angle Θ_{sk}. This skyrmion Hall effect has been directly observed in multilayer systems with spin–orbit torque driven skyrmion motion.[40,41]

The fact that skyrmions are small, stable, and respond to spin-polarized currents means that they are promising candidates for skyrmion spintronic devices. Understanding the mechanisms of creating, propagating, and detecting magnetic skyrmions at room temperature in devices by all-electrical means is an important stepping stone toward realizing novel applications. In Sec. III, we review our recent results on these three topics.

III. RECENT RESULTS

A. Nucleation

The room temperature stability and magnetic field-induced nucleation of skyrmions in interfacial DMI heterostructures are well-documented and are controlled by a balance of magnetic energy terms (exchange, DMI, anisotropy, Zeeman, and magnetostatic).[10,11] However, in real world devices, it is not only such material properties but also defects and inhomogeneities which play an important role.[42] The development of practical devices requires the controlled nucleation skyrmions at defined points of interest. Numerical investigations demonstrated the possibility of spin-polarized currents injected vertically as means to electrically nucleate individual skyrmions in nanostructures,[43] a concept later expanded upon using a point contact via micromagnetic simulations.[44] Experimentally, it was shown that divergent currents ($J \sim 10^9$–10^{10} Am^{-2}) combined with a small out-of-plane magnetic field can be used to create skyrmions at the point where the constriction expands into a wider wire. If the constriction is made from the same magnetic material, the nucleation mechanism is analogous to bowing soap bubbles, in so far, that the domains are pushed through the constriction by the current, expand as they leave the constriction, and then pinch off into skyrmions[15] [see Fig. 2(a)]. A more chaotic and less predictable creation mechanism is the electrical nucleation from random defects in nanostructures, which was observed by various groups in 2018 [see Fig. 2(b)].[45–47] In bulk systems, electrical nucleation has been demonstrated at current densities three magnitudes lower.[48] Hrabec *et al.* showed the first experimentally deterministic nucleation from a non-magnetic point contact driven by the divergence of current lines, heating, and spin accumulation at the tip, which results in the local reversal of the magnetic configuration near the tip[49,50] [see Fig. 2(c)].

Our work in 2019 took advantage of this idea to demonstrate the all-electrical nucleation of skyrmions in 4 ns at zero field using a 1.4×10^{12} Am^{-2} density, the 5 ns long current pulse is possible via

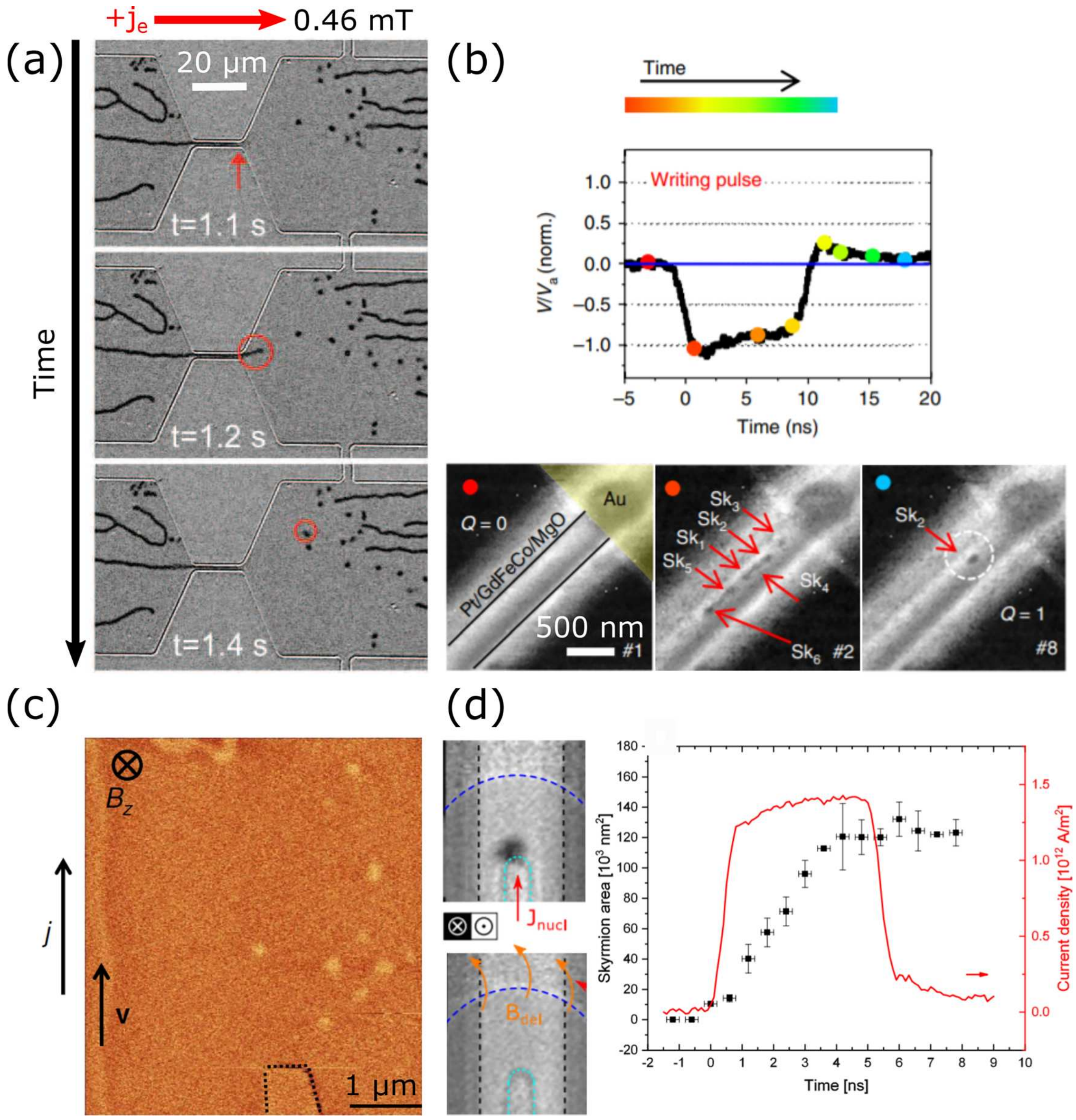

FIG. 2. Electrical nucleation of skyrmions in heterostructures. (a) Néel-type skyrmion nucleated using a current pulse from a geometrical constriction. Reprinted with permission from Jiang *et al.*, "Blowing magnetic skyrmion bubbles," Science **349**, 283 (2015). Copyright 2015 AAAS.[15] (b) Electrical nucleation at pinning sites. Reprinted with permission from Woo *et al.*, "Deterministic creation and deletion of a single magnetic skyrmion observed by direct time-resolved X-ray microscopy," Nat. Electron. **1**, 288 (2018). Copyright 2018 Springer Nature.[46] (c) Deterministic nucleation of skyrmions using a nanocontact. Reproduced from Hrabec *et al.*, "Current-induced skyrmion generation and dynamics in symmetric bilayers," Nat. Commun. **8**, 15765 (2017). Copyright 2017 Authors, licensed under a CC-BY License.[49] (d) Time resolved investigation of skyrmion nucleation from a point contact. Reprinted (adapted) with permission from Finizio *et al.*, "Deterministic field-free skyrmion nucleation at a nanoengineered injector device," Nano Lett. **19**, 7246–7255 (2019). Copyright 2019 American Chemical Society.[51]

spin-orbit torque (SOT)-induced local switching in a Pt/$Co_{68}B_{32}$/Ir microwire. A square current pulse was injected through a 500 nm wide Cu injector fabricated on top of the magnetic wire. The skyrmion was annihilated using an Oersted field generated from an Omega coil, which was fabricated in the vicinity of the injector. This setup enabled us to used time resolved microscopy to study the sub-nanosecond dynamics with a time resolution of 200 ps[51] [Fig. 2(d)]. The nucleation was highly deterministic, and the size of the nucleated skyrmion was determined in part by the total amount of charge in the current pulse, as well as, the length of the current pulse. No measurable delay was observed between the electrical excitation and the nucleation of a single skyrmion. Furthermore, we observed that in the absence of static external magnetic fields, the four possible combinations of the nucleation current direction and the annihilation field direction are symmetric. Both observations are indicative of SOT influenced magnetic switching. Dynamical heating of the microwire during the current pulse was seen to play a role in the magnetization reversal by raising the temperature of the wire during the pulse close to the Curie temperature (measured to be 475 K) and, thus, lowering the threshold current density needed to nucleate a skyrmion. The change in temperature during the current pulse was determined by correlating the magnetization dependent contrast change in the saturated area of the wire with the known saturation magnetization change of the multilayer (measured using SQUID-vibrating sample magnetometry). During the 5 ns pulse, the temperature was seen to increase to be around 420–440 K. Skyrmion nucleation can be even faster. Nucleation at the picosecond timescale was later demonstrated via femtosecond laser pulses, which demonstrated to be mediated by a high-temperature topological fluctuation state in which skyrmions are created by homogeneous nucleation.[52]

An alternative way of nucleating skyrmions at precise, customized locations is by artificially changing the magnetic energy landscape and breaking the symmetry of the system by, for example, introducing defects such as local fluctuations of the anisotropy, a process first suggested separately by Büttner *et al.*[53] and Everschor-Sitte *et al.*[54] in 2017. We have shown that focused ion beam (FIB) irradiation enables the localized and deterministic nucleation of skyrmions under external out of plane field cycling.[55] Ion irradiation is well-documented to both reduce the perpendicular anisotropy and increase the coercivity in a dose-dependent manner. This deterministic manipulation of the magnetic properties has multiple advantages (1) it enables the localization of nucleation; (2) it stabilizes skyrmions over a larger range of external field strengths, including stability at zero field; (3) it enables the existence of skyrmions in materials systems where, prior to defect fabrication, skyrmions were not previously observed through field cycling alone. By carefully tuning the artificial defect, it is possible to promote nucleation of skyrmions without changing the equilibrium diameter of the skyrmion. FIB defects were created using a FEI Nova NanoLab 200 SEM and FIB with a 30 keV Ga^+ beam energy and a beam current of 10 pA, resulting in an ion beam diameter of 10 nm. Irradiation doses between 10^{14} and 10^{18} ions per cm^2 were delivered to the sample. Intermixing of the top layers of the multilayer was observed at doses above 5×10^{16} ions per cm^2 with structural damage being introduced at doses above 10^{17} ions per cm^2. At the optimum doses, 100% skyrmion nucleation was observed without affecting the skyrmion diameter. The observed mean skyrmion diameter at zero field was measured to be 170 ± 30 nm nucleated at 5×10^{16} ions per cm^2 defects and 180 ± 30 nm at 1×10^{17} ions per cm^2 defects. From structural imaging, these ion irradiation doses were associated with a 100 nm diameter area of damage. More recently, it was shown that similar effects can be achieved using He^+ irradiation. By lowering the out of plane anisotropy and DMI strength locally along linear tracks, it was shown that skyrmions were preferentially nucleated and move along the "designer" tracks and with this a suppression of the skyrmion Hall effect was achieved.[56] Initial studies have expanded this concept toward active anisotropy control via strain engineering (in this instance via temperature). This is an exciting first step toward developing strain-assisted skyrmion-based memory and logic devices.[57] Strain manipulation is an innovative solutions for devices of the future, which reduces energy dissipation and the risk of heightened temperatures within the device caused by current pulses.[58]

B. Propagation

The first experimental demonstration of the electrically driven motion of skyrmions at ambient temperatures was reported by Woo *et al.* in Pt/Co/Ta and Pt/CoFeB/MgO-based multilayer microwires under an applied out-of-plane field.[16] Velocities of 46 ms^{-1} at current densities $J \sim 3.5 \times 10^{11}$ Am^{-2} were observed. Jiang *et al.* showed the skyrmion Hall angle, Θ_{sk}, evolution with velocity in Ta/CoFeB/TaO_x trilayers at velocities < 1 ms^{-1} and an external magnetic field.[40] Following the modified Thiele equation for rigid skyrmions, Θ_{sk} is expected to depend on the skyrmion diameter d, given by $\tan \Theta_{sk} = v_y/v_x = -Q/\alpha\mathscr{D}$, where v_y and v_x are the velocity of the skyrmion along y and x, respectively. The geometrical factor $\mathscr{D} = \pi 2d/8\gamma_{dw}$, where γ_{dw} is the width of the domain wall surrounding the skyrmion.[40] Note that this approach predicts that Θ_{sk} is independent of the driving force or velocity of the skyrmion, in contradiction to the experimental findings of both this group[40] and the work of Litzius *et al.*[41] This is because an idealistic flat energy landscape is assumed, and therefore there is no pinning force term in this form of the Thiele equation.

An early indication of the importance of the materials system and the amount of inhomogeneities and pinning sites present with respect to skyrmion motion (as well as nucleation[46]) were observed in the work of Woo *et al.* in 2016.[16] In our own work on skyrmion motion, we elaborated on this by demonstrating the skyrmion motion at zero field in a metallic CoB-based multilayer material system. We showed that the influence of inhomogeneities and skyrmion-skyrmion repulsion on the skyrmion motion driven by current pulses is crucial in understanding the observed skyrmion Hall angle.[59] We tracked hundreds of skyrmions with diameters ranging from 35 to 825 nm with an average velocity of 6 ± 1 ms^{-1}. We observed a diameter independent average skyrmion Hall angle of $9^\circ \pm 2^\circ$ [Fig. 3(a)]. This showed experimentally that in material systems with pinning and inhomogeneities, the diameter dependence of the skyrmion Hall effect is washed out and the direction of motion is often dominated, not by the topology, but by the micromagnetic environment[59] [Fig. 3(b)]. Furthermore, in the high skyrmion density regime, collective motion takes place where the presence of interfacial spin transfer torques can also weaken the diameter dependence.[60] Our experimental observations reproduce principles shown in skyrmion motion models and micromagnetic simulations throughout the literature[61,62] [Fig. 3(c)]. In addition, it was shown that in multilayer systems, it is crucial to consider the non-rigidity of the skyrmion during the current pulse. Depending on the current density, it is possible to observe skyrmion shape deformation, which occurs during the current pulses when using moderate current densities as well as skyrmion domain wall deformation, which occurs at large current densities. Both phenomena affect the skyrmion Hall angle.[41,63,64]

In more recent publications, further engineering of the magnetic energetic via careful tuning of the heterostructure material design has paved the way toward skyrmion motion, which is driven[65] and controlled by thermal and temperature gradients.[66] Studies in bulk systems, such as MnSi, showed thermally activated skyrmion-lattice-creep with important consequences for motion occurring at low J.[67]

C. Detection

Electrical detection is a key requisite for any skyrmion spintronics application. More fundamentally, owing to the non-trivial topology,

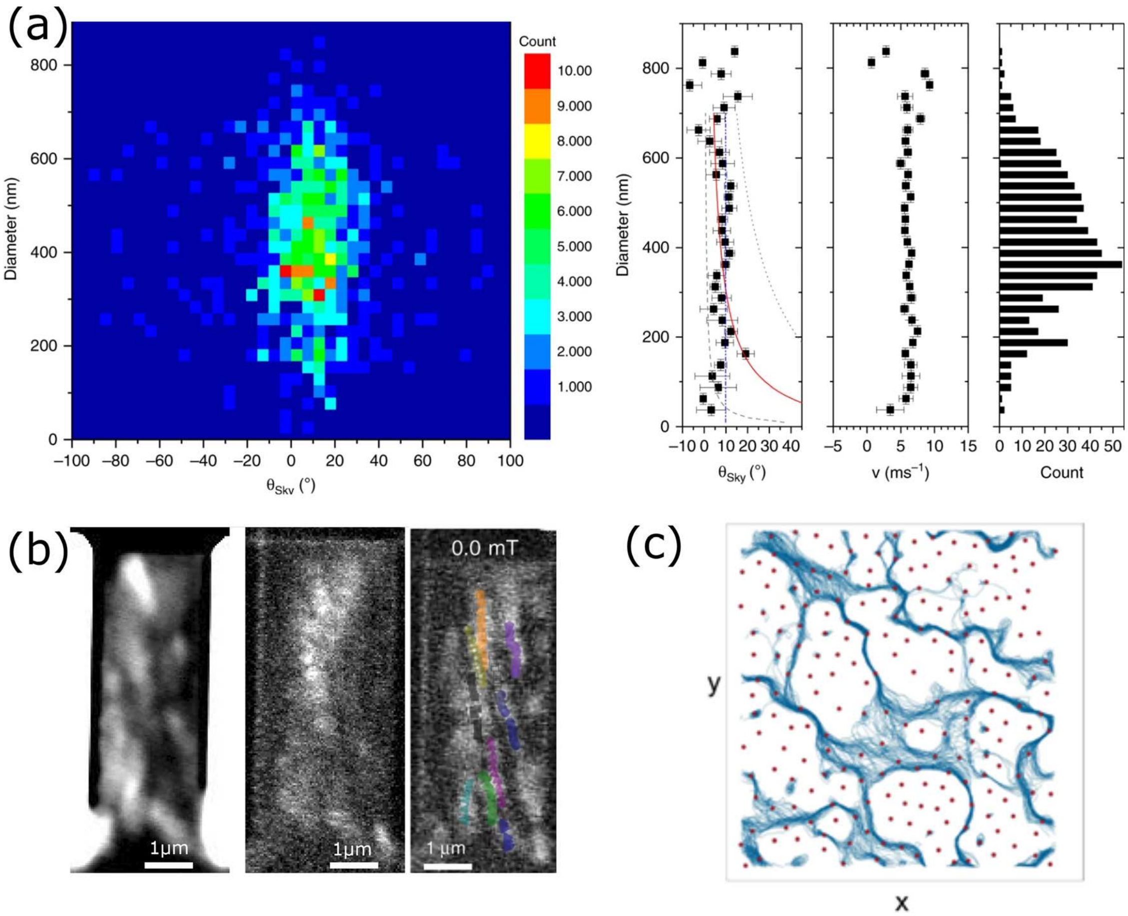

FIG. 3. Electrically driven motion of skyrmions in heterostructures. (a) Diameter dependence of the skyrmion Hall angle in an imperfect heterostructure. Reproduced from Zeissler *et al.*, "Diameter-independent skyrmion Hall angle observed in chiral magnetic multilayers," Nat. Commun. **11**, 428 (2020). Copyright 2020 Authors, licensed under a CC-BY License.[59] (b) Left, average intensity map of STXM images. Bright regions show areas with higher probability of skyrmion occurrence probability of containing a reversed magnetic domain or skyrmion. Middle, average intensity map of the absolute difference between consecutive images. Bright regions show high probability of a moving skyrmion. Reproduced Zeissler *et al.*, "Diameter-independent skyrmion Hall angle observed in chiral magnetic multilayers," Nat. Commun. **11**, 428 (2020). Copyright 2020 Authors, licensed under a CC-BY License.[59] (c) Simulated path taken by skyrmions moving at low velocities in a system containing an array of defects. Reproduced from C. Reichhardt and C. J. Olson Reichhardt, "Noise fluctuations and drive dependence of the skyrmion Hall effect in disordered systems," New J. Phys. **18**, 095005 (2016). Copyright 2016 Authors, licensed under a CC-BY License.[61]

the way a skyrmion interacts with electrons traversing it leads to a rich emergent electrodynamics.[33] As outlined in the introduction, a magnetic system containing skyrmions is expected to result in three distinct and dominant contribution to its resistance: (1) the ordinary Hall effect experienced by all conducting materials, (2) the anomalous Hall resistance, which is proportional to the systems out-of-plane magnetization, and (3) the topological Hall resistance. We can, therefore, write that $\rho_{xy} = R_{\mathrm{H}}B + R_{\mathrm{S}}\mu_0 M + R_{\mathrm{H}}PB_{\mathrm{e}}$, where R_{S} is the anomalous Hall coefficient [see Fig. 4(a)].

Looking at the electrical detection, it was shown by Maccariello *et al.* that skyrmions can be measured using the anomalous Hall effect. A electrical signature of a single skyrmion with a diameter of $<$100 nm was measured to be of the order of 3.5 ± 0.5 nΩcm.[47] However, using the anomalous Hall resistance in systems where the skyrmion size is not constant is open to interpretation errors if the skyrmion diameter is not uniform, as differentiating between a large skyrmion and multiple smaller skyrmions is impossible if the ratio of antiparallel aligned magnetized domains is identical. In principle, the topological Hall effect allows us to make this distinction. For example, in FeGe nanostructures containing a magnetic crystal of skyrmions, the quantized jump associated with each skyrmion was measured to be $\sim$10 nΩcm.[68] In interfacial skyrmion systems, similar skyrmion number-dependent contributions have been observed. Soumyanarayanan *et al.* published a skyrmion density dependent resistivity contribution of $\rho_{xy} = 30$ nΩcm in films of Ir/Fe/Co/Pt heterostructures.[12] Our work in Pt/Co/Ir multilayer systems showed that there is indeed a skyrmion number dependent quantized resistivity contribution in interfacial Neel skyrmions of 22 ± 2 nΩcm. We measured the resistivity of individual skyrmions in a disk while simultaneously imaging the out-of-plane magnetization[45] [see Figs. 4(b)–4(e)]. However, this is three

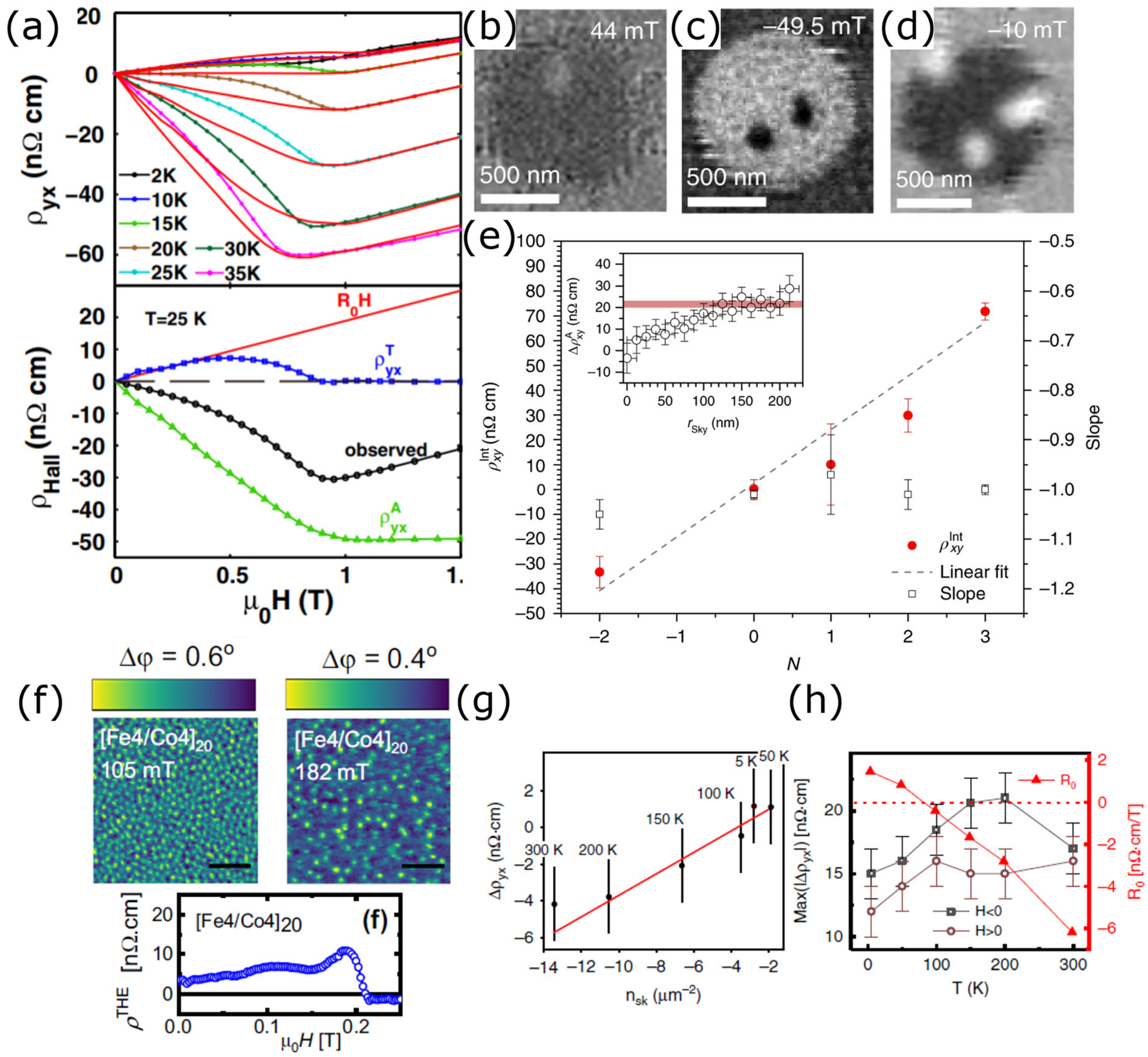

FIG. 4. Electrical detection of skyrmions. (a) Changes in the resistivity as the MnSi bulk crystal passes through the skyrmion phase. Bottom panel shows the different contribution to the resistivity (ordinary Hall resistivity, anomalous Hall resistivity, and topological Hall resistivity). Reprinted with permission from Li *et al.*, "Robust formation of skyrmions and topological hall effect anomaly in epitaxial thin films of MnSi," Phys. Rev. Lett. **110**, 117202 (2013). Copyright 2013 American Physical Society.[73] (b)–(d) Scanning transmission x-ray microscopy showing the out of plane magnetic contrast of one, two, and three skyrmions in an electrically connected disk (light and dark contrast show antiparallel aligned magnetic domains).[45] (e) A quantized contribution to the resistivity, ρ_{xy}^{int}, which is independent of the magnetization but dependent on the number of skyrmions within the disk, the slope shows the skyrmion size dependent anomalous Hall resistance, which is directly proportional to the ratio between the up and down magnetized domains.[45] The inset shows that the skyrmion number dependent contribution becomes significant for skyrmions with radius below around 125 nm (f)–(g) Magnetic force microscopy images of a Ir/Fe/Co/Pt multilayer system driven from the skyrmion lattice into the metastable isolated skyrmion phase and the measured increase in the topological Hall contribution. Reproduced from Raju *et al.*, "Colossal topological Hall effect at the transition between isolated and lattice-phase interfacial skyrmions," Nat. Commun. **12**, 2758 (2021). Copyright 2021 Authors, licensed under a CC-BY License.[70] (g) Temperature dependence of the skyrmion density with temperature and the measured resistivity contribution not accounted for by the ordinary Hall resistivity and the anomalous Hall resistivity at -0.3 T $\Delta\rho_{xy}$. (h) Magnitude of the topological Hall resistivity peaks at negative (squares) and positive fields (circles) (left axis) in comparison to the temperature evolution of the ordinary Hall coefficient R_0 (right axis). Reproduced from Raju *et al.*, "The evolution of skyrmions in Ir/Fe/Co/Pt multilayers and their topological Hall signature," Nat. Commun. **10**, 696 (2019). Copyright 2019 Authors, licensed under a CC-BY License.[69]

magnitudes larger than the expected topological Hall resistivity using the Berry phase theory developed for bulk systems (discussed in the introduction), which predicts a contribution of 0.01 nΩ cm per skyrmion, a conclusion that was mirrored and expanded in the study of Raju *et al.* in 2019.[69] The latest development in the investigation of this phenomenon was published in 2021 by Raju *et al.*, who showed that the unusually large topological resistivity values are measured for isolated skyrmions, whereas dense skyrmion arrays result in smaller topological resistivities[70] [see Fig. 4(f)]. A close link between the phase boundary of a dense skyrmion crystal and an isolated skyrmion system and the topological Hall effect was observed leading to a peak of the topological contribution followed by a sharp decline as all skyrmions are annihilated within the material system. A strong dependence on the stability parameter $\kappa = \pi D/\left(4\sqrt{AK_{\text{eff}}}\right)$ was found. The value of $\kappa < 1$ represents a disordered metastable skyrmion phase, and $\kappa \geq 1$ represents a skyrmion lattice phase. Field and temperature were used to show the dependence of the topological Hall signal on κ by driving the material system from the skyrmion lattice phase into the isolated skyrmion phase and vice versa. The complicated relationship between the topological Hall resistivity theory and the measurements in heterostructures is emphasized in Fig. 4(g), which shows a linear dependence of the topological Hall resistivity with temperatures and skyrmion densities. Furthermore, Fig. 4(h) shows a less than 25% change in the topological Hall resistivity while the ordinary Hall coefficient changes sign.[69] Raju *et al.* concluded that chiral spin fluctuations at all length scales, which occur at the phase boundary, cause the colossal magnitudes of the topological Hall effect in chiral magnetic heterostructures.[70] Other chiral scattering effects have been predicted by Lux *et al.*[71] and Fujishiro *et al.*,[72] with the latter also being used to account for the observation of a giant anomalous Hall effect in a MnGe thin film. Studying the relevance of the new mechanisms to skyrmion spintronic materials is a future direction for research.

For practical applications, however, larger changes in the resistivity are desirable. For this, magnetic tunnel junctions are a powerful sensing device for skyrmions. In 2019, it was shown that a single skyrmion with a diameter less than 100 nm resulted in a change in the magnetic tunnel junction resistance of around 10%.[74]

IV. OUTLOOK

The field of skyrmion spintronics continues to be a lively one with many open questions to answer and active avenues of research to pursue. For instance, in term of materials and pinning—what are the desired parameters for different applications? CMOS-compatibility imposes a lot of requirements and restrictions with regard to what materials are feasible and how they are grown. Other applications might be more open. Post materials growth refinement is an interesting avenue with many possibilities. For example, it has recently been shown that He irradiation can be used to locally reduce pinning, allowing the creation of tracks along which skyrmions propagate[56] [see Fig. 5(a)].

In Sec. III, we have principally discussed manipulating skyrmions using spin–orbit torques. Nevertheless, other forms of electrical nucleation and propagation are possible. For instance, micron-scale skyrmion bubbles were observed to appear in a Pt/Co/oxide trilayer beneath an indium tin oxide electrode when +20 V was applied,[79] attributed to a voltage-driven change in the Curie temperature causing a modulation of M_s. In similar experiment using a multilayer with a lateral thickness gradient, the application of the voltage caused skyrmions to both appear and then begin to move along the gradient direction.[80] In modeling this process, it was assumed that the voltage causes changes in the perpendicular magnetic anisotropy (PMA), an effect that has come to be known as voltage-controlled magnetic anisotropy (VCMA). VCMA has been exploited to create and annihilate skyrmions by means of nanosecond voltage pulses in a magnetic tunnel junction that was used to detect them by tunneling magnetoresistance[81] or to create and annihilate skyrmions at zero field in a multilayer in which an antiferromagnetic layer was used to apply an effective field using exchange bias.[82] Simulations have been used to show that the VCMA effect is suitable for operating voltage controlled memory elements based on skyrmions that are potentially much more energy efficient than alternatives based on spin–orbit torques.[83]

As well as the direct effects of electric fields on magnetic properties, there are indirect effects such as those mediated by strain via the electric field induces strain in a piezoelectric material that forms an interface with the magnetic layer of interest. Transfer of strain across the interface induces magnetic effects through magnetostriction. Simulations of magnetic nanodisks showed that strain-mediated nucleation and annihilation of skyrmions are possible, as well as controlling a range of other topological transitions between skyrmions, vortices, merons, and skyrmioniums.[84] In another simulation, a single stable skyrmion was created and stabilized by a vertical strain pulse applied to a Pd/Fe/Ir hybrid structure generated by a piezoelectric $Pb(Zr_{1-x}Ti_x)O_3$ nanowire.[85] In a more advanced approach, which takes account of biaxial as well as uniaxial strain, a combination of multiscale modeling and Lorentz microscopy was used to demonstrate deterministic control over topological spin textures in magnetic thin films.[86] An interesting form of applying a non-uniform strain is the traveling strain wave known as a surface acoustic wave (SAW). Simulations incorporating magnetoelastic phenomena show that skyrmions can move in response to SAWs.[87] Furthermore, there is now an experimental report of skyrmions being created using SAWs.[88]

How small can skyrmions be made? High density storage applications rely on having the smallest possible bit sizes. While nanometer-scale skyrmions are possible in epitaxial ferromagnetic monolayers at cryogenic temperatures,[89] theoretical considerations point to low or zero moment materials as offering the best opportunities for success at room temperature.[90] One approach is to use rare earth-transition metal ferrimagnetic alloys close to their compensation point, where skyrmions approaching sizes as small as 10 nm have been observed[75] [see Fig. 5(b)]. An additional benefit of these materials is the suppressed skyrmion Hall effect[46] (predicted via theory by Barker and Tretiakov[91]) due to the cancelation of the equal and opposite topological charges on the two sublattices.

However, one drawback of this approach is the relatively narrow window of operating temperatures, which is restricted to a small region around the compensation point. Given the experimental difficulties of working with true antiferromagnets, another way of achieving a net zero magnetization is to use synthetic antiferromagnets,[90,92] where pairs of equal moment ferromagnetic layers are coupled though spacers that provide an antiferromagnetic indirect exchange interaction.[93] Recent experiments have separately shown that skyrmions in such systems can be small,[94] dense,[95] and have negligible skyrmion Hall effects.[96]

How else can skyrmions be stabilized other than the DMI? Much recent activity has focused on the idea of frustration being another mechanism.[97–99] The dynamics of skyrmions stabilized by this method has been studied by micromagnetic simulation.[100,101] Experimentally, a promising material for studying these phenomena is the frustrated Kagomé ferromagnet Fe_3Sn_2, which has been shown to host skyrmions at room temperature.[8] The fact that there is no DMI to enforce a single chirality for these skyrmions means that the two possible chiral states might be used to represent a digital 0 and 1 rather than presence and absence. Bit control is achieved through the current-driven helicity switching.[100,102] Experimental progress already shows promise

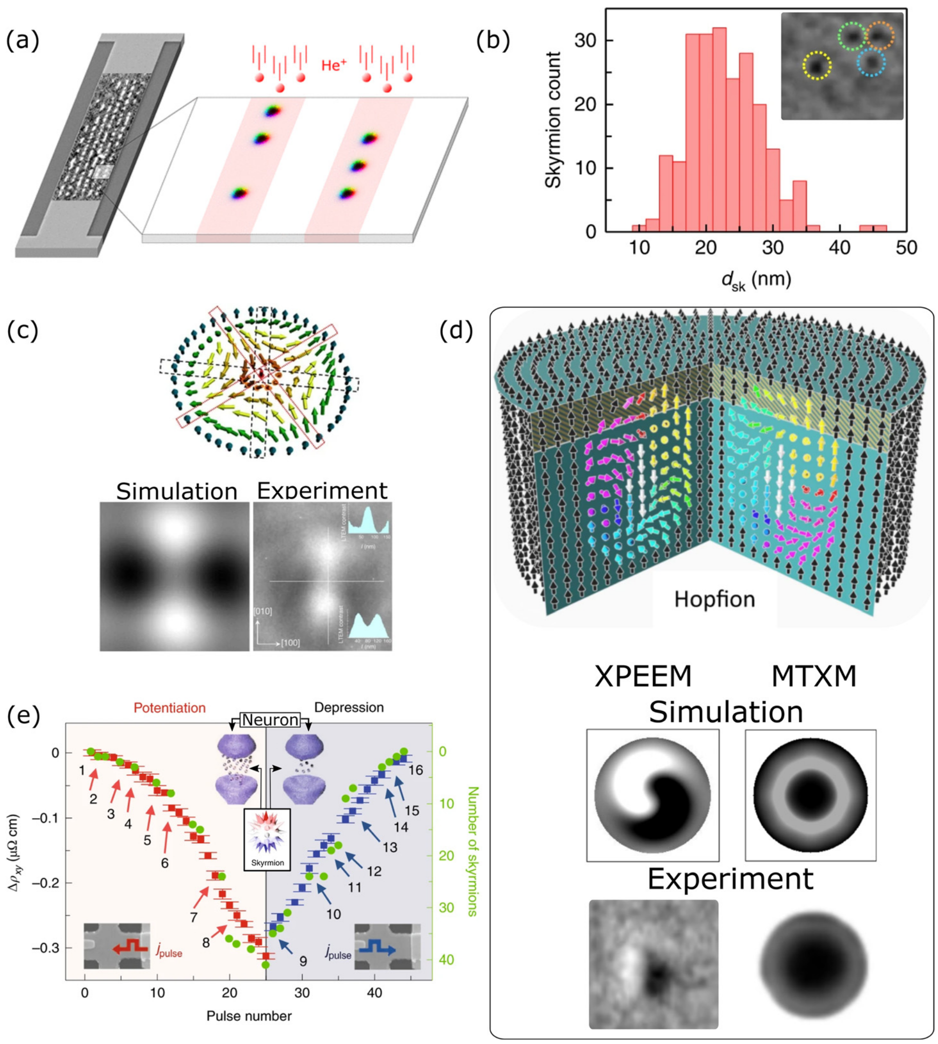

FIG. 5. What does the future hold for the field of skyrmion research? (a) Putting skyrmions on track using helium ion irradiation. Reprinted (adapted) with permission from Juge *et al.*, "Helium ions put magnetic skyrmions on the track," Nano Lett. **21**, 2989 (2021). Copyright 2021 American Chemical Society.[56] (b) Moving toward smaller skyrmions stable at room temperature. Reprinted with permission from Caretta *et al.*, "Fast current-driven domain walls and small skyrmions in a compensated ferrimagnet," Nat. Nanotechnol. **13**, 1154 (2018).[75] Copyright 2018 Springer Nature. (c) Discovering new materials supporting antiskyrmions. Reprinted with permission from Nayak *et al.*, "Magnetic antiskyrmions above room temperature in tetragonal Heusler materials," Nature **548**, 561–566 (2017). Copyright 2017 Springer Nature.[76] (d) Entering the rich space of three dimensional topological quasi particles with hopfions. Reproduced from Kent *et al.*, "Creation and observation of hopfions in magnetic multilayer systems," Nat. Commun. **12**, 1562 (2021). Copyright 2021 Authors, licensed under a CC-BY License.[77] (e) Using skyrmions for non-von Neumann computing hardware. Reprinted with permission from Song *et al.*, "Skyrmion-based artificial synapses for neuromorphic computing," Nat. Electron. **3**, 148–155 (2020). Copyright 2020 Springer Nature.[78]

for memories,[103] where the unusually large topological Hall effect in this material might be useful for readout.[104]

What other topological spin textures could provide spintronic functionality? Other topological objects, e.g., antiskyrmions, skyrmioniums, and hopfions, are coming to the attention of researchers working in magnetism.[105] An anisotropic DMI can lead to the formation of antiskyrmions,[106] where the form oscillates twice between Bloch and Néel as the edge of the structure is traversed. Lattices of antiskyrmions have been observed in ferromagnetic $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$,[76] ferrimagnetic $Mn_2Rh_{0.95}Ir_{0.05}Sn$[107] [see Fig. 5(c)], and $Fe_{1.9}Ni_{0.9}Pd_{0.2}P$.[108] Clever selection of the current direction with respect to the DMI anisotropy axes can be used to control their direction of motion.[108,109] Furthermore, they generate topological Hall signals in the same way as skyrmions.[110]

A skyrmionium is one skyrmion contained within another of opposite topological charge[111] and hence possesses zero net gyrovector.[112] These structures are also known as target skyrmions. Simulations show that they have distinctive current-[113] and field-driven dynamics[114] and have recently been observed in FeGe nanodiscs.[115]

In three-dimensions, skyrmion tubes that are twisted into rings and knots known as hopfions have been predicted to exist, possessing their own topological index called the Hopf charge.[116] Micromagnetic modeling shows that these can be expected to be stabilized in chiral magnetic nanodiscs.[116,117] The same approach has been used to model the dynamics. While there is no gyrovector ($\mathbf{G} = 0$) and, therefore, no equivalent of the skyrmion Hall effect is to be expected, the dynamics is rich! It is predicted that the form of the hopfion (Néel or Bloch-like) will affect the direction of travel under current drive.[118] The three-dimensional nature of these objects means that other degrees of freedom, such as rotation and dilation, are also available.[119] Very recently, a simple form of a hopfion has been experimentally detected in a multilayer nanodisc, in which the ferromagnetic Co layer thickness was varied to give a depth dependent magnetic anisotropy[77] [see Fig. 5(d)].

Beyond the ubiquitous racetrack memory concept,[120,121] what possible applications might there be that use the unique properties of skyrmions? Various proposals for skyrmion-based logic architectures exist that can perform Boolean operations,[122] can be reconfigurable,[123] and provide reversible computing[124] or logic-in-memory operation.[125]

Unconventional (non-von Neumann) computing is rapidly becoming one of the most promising application areas for spintronics with neuromorphic computing being a particular focus.[126] A proposal for the use of a skyrmion gas for probabilistic computing[127] was recently realized experimentally.[65] Combining this concept with logic-style networks allows for stochastic computing using skyrmions.[128] Meanwhile, related skyrmion textures are potentially useful for reservoir computing[129,130] and random number generation.[131] The unique properties of skyrmions have also been proposed as a means to realize synaptic devices.[132,133] The current-driven nucleation, propagation, and detection of skyrmions have been shown to mimic synaptic potentiation and depression in a ferrimagnetic nanoscale device suitable for neuromorphic applications such as image recognition[78] [see Fig. 5(e)]. Skyrmion networks can be used to provide a solution to the shortest path problem.[134]

There are also possibilities in the realm of quantum technology. A skyrmion-bearing layer placed on top of a superconductor is predicted to host a Majorana bound state at its core[135,136] or to generate Majorana bands around the edge of the skyrmion.[137] Suitable materials systems have already been fabricated.[138] For sufficiently small skyrmions, the chirality can possess quantum dynamics,[139] leading to a recent proposal that skyrmions can be used as qubits.[140]

From this rich variety of current and future research directions, it is clear that skyrmion spintronics will continue to be an active and vibrant field for many years to come.

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AUTHOR DECLARATIONS

Conflict of Interest

We have no conflicts of interest to declare.

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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