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ABSTRACT
Magnetic skyrmions are a new form of magnetic ordering with whirlpool-like spin arrangements. These topologically protected particlelike spin textures were first discovered a decade ago in noncentrosymmetric magnetic materials. Confining magnetic skyrmions in nanostructures leads to interesting fundamental insights into skyrmion stability and could provide convenient platforms for potential practical applications of skyrmions in information storage technology. In this research update, we summarize the recent advances on studying magnetic skyrmions in nanostructures of skyrmion hosting noncentrosymmetric materials (especially the B20 materials) made via bottom-up synthesis or top-down fabrication methods. We discuss various real space imaging (such as Lorentz transmission electron microscopy or electron holography) or physical property measurement (such as magneto-transport) techniques that have been used to observe and detect these exotic magnetic domains in both nanostructure and bulk samples, which have proven to be critical to fully understanding them. We examine the importance of morphology and dimensionality of skyrmion hosting materials in stabilizing isolated magnetic skyrmions in confined geometry and their benefits for implementation in magnetic memory applications. We further highlight the need for experiments that allow the skyrmion research to move from the fundamental physics of skyrmion formation and dynamics to more applied device studies and eventual applications, such as the all-electrical writing and reading of skyrmions needed for skyrmion-based high density magnetic memory storage devices.

I. INTRODUCTION
Understanding the role of topology in materials science and condensed matter physics has become an exploding field of research in the last few decades. A new page in this field was turned in 2009 with the experimental discovery of topologically protected particle-like spin textures known as magnetic skyrmions found in a single crystal of cubic B20 noncentrosymmetric magnetic material. This name originates from the Skyrme model that was developed in nuclear physics to describe configurations of stable localized particle-like excitations in field theory. Skyrmions are exotic vortex-like magnetic spin textures in which the central spin is antialigned and the outer spins are aligned with the externally applied magnetic field [Fig. 1(a)]. The noncollinear spin structures, such as helimagnetic, conical [Fig. 1(b)], and skyrmion orderings, are most commonly a result of a direct thermodynamic competition between the ferromagnetic exchange interaction and the Dzyaloshinskii-Moriya exchange interaction (DMI). The arrangement of spins within a single skyrmion can wrap a sphere, which is generally characterized with nonzero topological charge known as the skyrmion winding number \( w \) defined by

\[
w = \frac{1}{4\pi} \int n \cdot \left( \frac{\partial}{\partial x} n \times \frac{\partial}{\partial y} n \right) d^2 r, \quad n = m/|m|, \tag{1}\]

where \( m \) is the local magnetic moment. Based on the integral value of the skyrmion number and symmetry of the crystal structure, topologically nontrivial spin textures including magnetic skyrmions could have different internal spin arrangements. A skyrmion lattice and nanometer size skyrmion domain were first reported for a Bloch-type skyrmion which was experimentally found in metal monosilicides with a noncentrosymmetric B20 crystal structure [Fig. 1(c)].
This first experimental observation of magnetic skyrmions was in a single crystal of MnSi with the cubic B20 crystal structure using small angle neutron scattering (SANS). These experiments revealed scattering patterns with 6-fold symmetry in the temperature and magnetic field region of the so-called "A-phase" (magnetic skyrmion phase) of MnSi [Fig. 1(d)]. The circular domains of magnetic skyrmions arrange into a hexagonal lattice, which leads to this scattering pattern with 6-fold symmetry. SANS experiments at different applied magnetic fields and temperatures allowed for the mapping of the entire magnetic phase diagram of MnSi below the helimagnetic transition temperature, $T_c$. The magnetic phase diagram of MnSi, like other skyrmion hosting materials, includes many complex magnetic phases including the helimagnetic, conical, field-polarized, as well as the magnetic skyrmion [Fig. 1(e)].

The periodicity of the noncollinear spin texture is defined by the ratio of the ferromagnetic exchange and DMI strengths, where an increasing DMI will lead to a shorter spin structure periodicity. However, for a nonzero DMI to exist, the material at hand must lack inversion symmetry. Noncentrosymmetric B20 cubic crystal structures (space group: $P_{21}3$), such as the metal monosilicides, monogermandies, and their alloys that include MnSi, Fe$_{1-x}$Co$_x$Si, FeGe, and MnGe, fulfill this requirement due to their atomic arrangements [Fig. 1(c)]. The intrinsic DMI produced by the noncentrosymmetric crystal structure due to spin-orbit interaction, also known as bulk DMI, gives rise to a relatively large DMI strength which leads to a periodicity of less than 100 nm for both the helimagnetic and skyrmion phases. The overall symmetry of the crystal system leads to the formation of a chiral Bloch-type skyrmion with a vortexlike spin structure that can be visualized in real space using magnetic contrast imaging techniques such as Lorentz transmission electron microscopy (LTEM) [Fig. 1(f)]. However, the window of the applied magnetic field and temperature where the skyrmions exist is drastically different in the various cubic B20 compounds. These stability windows in each of the magnetic phase diagrams of each known skyrmion material have been mapped using some combination of SANS, magnetic contrast imaging, and/or magnetic susceptibility measurements as discussed later.

The domain size of skyrmions formed by the bulk DMI is generally less than 100 nm and down to 3 nm depending on the material. The ability of the magnetic skyrmion domain to form in such small
sizes compared to ferromagnetic domains is likely tied to the topology of the spin structure that prevents them from being destroyed by small variations in the applied magnetic field and temperature. The topological protection, thermal stability, and small magnetic domain of the skyrmion are of interest to magnetic information storage research. Therefore, the skyrmion domain size, $a_{sk}$, provides an opportunity to break the so-called super paramagnetic limit of magnetic storage using ferromagnetic domains. Superparamagnetism is common in most magnetic nanoparticles and results in ferromagnetic materials losing their ability to maintain the permanent magnetization required for nonvolatile magnetic information storage devices. In addition to their small domain size, the long-range modulation of the spins within the skyrmion relative to the underlying atomic lattice allow these quasiparticles to effectively decouple from the lattice so that they can move under small applied electric currents and/or thermal gradients. These advantages make skyrmions promising candidates for the replacement of ferromagnetic domains in the magnetic memory design known as magnetic racetrack memory.

In a conventional racetrack memory device, the ferromagnetic domains are translated as bits along a track by the electric current from “write” to “read” via a spin transfer torque mechanism [Fig. 2(a)]. This memory design can be utilized to pattern a high density of information that can be accessed quickly with smaller power consumption (like the dynamic random access memory devices) compared to current technologies such as magnetic hard disk drive (HDD) and FLASH memory. However, the current density needed to move the magnetic domains is very high ($10^{10} - 10^{11}$ A m$^{-2}$), which generally causes nanoscale device failure due to Joule heating. The magnetic skyrmions in B20 materials require about ~4 orders of magnitude less current density ($10^{6} - 10^{7}$ A m$^{-2}$) to translate than their ferromagnetic domain counterpart; therefore, they could solve this issue while also shrinking the domain size considerably. In addition, the emergent magnetic field generated by the skyrmion texture can give rise to a unique electronic signature for skyrmions known as the topological Hall effect (THE) [Fig. 2(b)] which can be detected by a classical Hall bar device architecture. Even with all the advantages, before the application of skyrmions could be realized in any envisioned magnetic storage device such as the magnetic racetrack memory device design shown in Fig. 2(c), there are still many scientific and technological challenges that need to be solved.

To explore skyrmions for potential magnetic storage, the study of the stability and dynamics of skyrmions in nanoscale skyrmion-hosting systems is crucial. Nanowires (NWs) have many advantages over bulk crystals or thin films—most important of which is that a NW geometry should stabilize the skyrmion phase more than in...
the bulk and thin film systems which were experimentally shown in MnSi [Figs. 3(a)–3(c)] and other B20 systems. As the dimension of the system approaches the size of the skyrmion domains, the conical magnetic configuration will be destabilized energetically compared to the skyrmion state. Along with the confinement stabilization of the skyrmion phase, a NW can also act as a natural “racetrack” and waveguide for the skyrmion motion and presents a convenient geometry for prototype device work. Moreover, the NW’s small cross section could facilitate the study of these prototype devices and emergent electrodynamics of skyrmions at much larger current densities. Therefore, NW systems can be utilized to study the skyrmion dynamics and manipulate skyrmions on even faster timescales.

To investigate the interesting skyrmion physics in materials, solid-state chemistry has proven to be instrumental in developing synthesis techniques for skyrmion hosting materials. Chemical methods for synthesizing skyrmion hosting single-crystal NWs and other nanostructures of metal silicides and germanides have been developed over the last 15 years. Chemical vapor deposition (CVD) and chemical vapor transport (CVT) syntheses have proven to be successful in growing nanostructures of the skyrmion-hosting B20 monosilicides such as MnSi, and alloys of FeSi and CoSi, such as Fe_{1-x}Co_{x}Si [Figs. 3(d)–3(g)]. These NWs feature rhombohedral cross sections split by a merohedral twin plane that partitions the NW into two parts of opposite chirality (left and right handiness) with NW growth along the [110] crystallographic direction [Figs. 3(e)–3(g)], which is characteristic of the chiral B20 crystal system (space group $P\overline{2}_13$). Nanostructures of B20 germanides such as FeGe and their alloys with a controllable amount of cobalt doping (e.g., Fe_{1-x}Co_{x}Ge) have been synthesized using CVD techniques as well [Figs. 3(h)–3(k)]. These synthetic methods generally can also produce unconventional shapes of geometrically confine nanostructures such as nanorods, nanoplates, and nano-octahedra, which can provide unique opportunities to observe the evolution of spin textures in skyrmion hosting systems. Of course, nanostructures can also be top-down fabricated using a focused-ion beam (FIB) from bulk crystals (as discussed in Sec. IV B) or MBE growth thin films. However, further processing is still needed for making 1D racetracks or other low-dimensional nanostructures.

In this research update, we highlight the recent progress in the studies of magnetic skyrmions in NWs and other nanostructures of noncentrosymmetric B20 materials. We first discuss the methods of observation and detection of skyrmions in chiral B20 materials.

**FIG. 3.** Magnetic skyrmion stability in B20 nanostructures and the crystal morphology of B20 NWs and various bottom up synthesized nanostructures grown via CVD growth. Magnetic phase diagrams showing the skyrmion phase stability of (a) bulk crystals, (b) thin plate, and (c) nanowire samples of MnSi, respectively. (d) SEM image of a MnSi NW with a smooth (111) surface and ⟨110⟩ growth direction. (e) A cross-sectional TEM image of the MnSi NW with a merohedral twin boundary, where the (001) twin plane is parallel to the ⟨110⟩ growth direction. (f) High-resolution TEM image of the cross section at the twin boundary. CVD grown (g) well faceted Fe_{1-x}Co_{x}Si micro/nanowires along the ⟨110⟩ growth direction and (h) the FeGe NW along the ⟨111⟩ growth direction. Nonconventional morphology such as (i) nanoplates, (j) nano-octahedra, (k) nanorods of FeGe B20 nanostructures grown using the CVD process. [Panels (a)–(c) are reproduced with permission from Yu et al., Nano Lett. 13, 3755 (2013), Copyright 2013 ACS. Panels (d)–(f) are reproduced with permission from Du et al., Nat. Commun. 6, 7837 (2015), Copyright 2015 Springer Nature Limited. Panel (g) is reproduced with permission from Mathur et al., ACS Nano 13, 7833 (2019), Copyright 2019 ACS. Panels (h), (j), and (k) are reproduced with permission from Stolt et al., Nano Lett. 17, 508 (2017), Copyright 2017 ACS. Panel (i) is reproduced with permission from Stolt et al., Adv. Funct. Mater. 29, 1805418 (2019), Copyright 2019 Wiley-VCH.]
with the bulk DMI. We do not attempt to discuss in detail the magnetic skyrmions formed by the interfacial DMI in various multilayer thin films, which is available in previously published reviews.\textsuperscript{45-51} For an overview related to general transport studies of skyrmions in bulk B20 materials, we refer to Refs. 2 and 52. Here, we focus on the importance of skyrmions in B20 nanostructures, which is conducive for studies related to geometric confinement and stability of skyrmions. We summarize the knowledge on the impact of morphology and dimensionality of skyrmion hosting materials in stabilizing isolated magnetic skyrmions in a confined geometry and the benefits for implementation in magnetic memory applications. This research update also brings attention to the detection of individual or clusters of confined skyrmions by solely electrical means which could be integrated with writing and reading device components for prototypes of the envisioned skyrmion-based racetrack memory devices.

II. SPIN TEXTURES AND CRYSTAL SYMMETRY

There exists a unique relationship between the interaction of the atomic spin and crystal symmetry. Of all the known compounds with the cubic B20 crystal structure, only MnSi, Fe\textsubscript{1-x}Co\textsubscript{x}Si, Fe\textsubscript{3}Ge, MnGe, Cu\textsubscript{2}OSeO\textsubscript{3}, and their alloys have been identified as materials that can host Bloch-type magnetic skyrmions. Other materials with the nonzero DMI due to polar symmetry breaking by the asymmetric layer stacking type magnetic skyrmions. Other materials with the nonzero DMI and the formation of Néel-type skyrmions which have been observed in single crystals of the GaV\textsubscript{8}Sn\textsubscript{8} material. GaV\textsubscript{8}Sn\textsubscript{8} has a noncentrosymmetric crystal structure like the B20 compounds; however, its crystal symmetry is of the R3\textit{m} space group instead of the P2\textsubscript{1}3 space group, and this leads to the formation of Néel instead of Bloch skyrmions.\textsuperscript{73} More recently, other skyrmion hosting materials with the bulk DMI have also been identified. For example, the Co-Zn-Mn family of compounds with the β-Mn structure (space group P4\textsubscript{1}32 or P4\textsubscript{1}32) host traditional Bloch-type skyrmions well above room temperature with \( T_c > 300 \) K, including some examples with \( T_c \) up to around 400 K.\textsuperscript{74} Other β-Mn structures of alloy Fe\textsubscript{2}Co\textsubscript{1-x}Rh\textsubscript{2}Mo\textsubscript{3}N\textsubscript{2} also host Bloch-type skyrmions which are stable up to \( \sim 115 \) K.\textsuperscript{75} Magnetic skyrmions with slightly varying, but still topologically protected spin textures can also be formed when the ferromagnetic exchange interaction competes with magnetic interactions other than the DMI. Interestingly, Fe\textsubscript{3}Sn\textsubscript{2}, with a kagome lattice structure, has centrosymmetric crystal symmetry and therefore no bulk DMI, but it is able to form skyrmions through long range dipole-dipole interactions, which end up producing skyrmions with a ringlike state with high ordering temperature, 630 K.\textsuperscript{76} Like Fe\textsubscript{3}Sn\textsubscript{2}, Mn-Ni-Ga alloys (space group P6\textsubscript{3}3/mmc) also form skyrmions through long range dipole-dipole interactions, but Mn-Ni-Ga alloys host type-II bubble domains instead of ring skyrmions; they comprise two skyrmions of opposite helicity merged together which are stable up to \( \sim 350 \) K in Mn-Ni-Ga alloys.\textsuperscript{77} In both cases, the lack of the bulk DMI as the source of skyrmion formation results in quite large magnetic domain sizes >100 nm. The most recent discovery in the skyrmion field is of antiskyrmions hosted by tetragonal Heusler alloys with D\textsubscript{2d} crystal symmetry of Mn\textsubscript{1–x}Pt\textsubscript{x}P\textsubscript{3}Sn\textsubscript{1} (space group, P-42m),\textsuperscript{78} which are stable up to \( \sim 400 \) K and have a nontrivial topological spin texture completely unique to the antiskyrmion state. However, in these systems, the relatively weak dipole-dipole interaction also leads to a slow periodic rotation of neighboring spins, resulting in skyrmions with sizes between \( \sim 100 \)s and 1000s nm, much larger than the skyrmions typically found in B20 materials. These materials are summarized in Table I. Apart from skyrmion spin textures in B20 materials, other 3D spin textures such as hedgehog lattice state and chiral bobbers (ChBs) are also observed in MnGe\textsuperscript{13,57} and FeGe,\textsuperscript{79} respectively.

| Material          | Space group (C = centrosymmetric, NC = noncentrosymmetric) | \( T_c \) (K) | Skyrmion domain size (nm) | Skyrmion type       |
|-------------------|----------------------------------------------------------|--------------|---------------------------|---------------------|
| MnSi\textsuperscript{1} | P2\textsubscript{1}3 (NC)                              | 28           | 18                        | Bloch               |
| Fe\textsubscript{0.5}Co\textsubscript{0.5}Si\textsuperscript{4,6} | P2\textsubscript{1}3 (NC)                              | 36           | 90                        | Bloch               |
| FeGe\textsuperscript{2}          | P2\textsubscript{1}3 (NC)                              | 278          | 78                        | Bloch               |
| MnGe\textsuperscript{13}         | P2\textsubscript{1}3 (NC)                              | 150          | \( \sim 5.5 \)            | Bloch (3D hedgehog) |
| Cu\textsubscript{2}OSeO\textsubscript{3} \textsuperscript{58} | P2\textsubscript{1}3 (NC)                              | 59           | 62                        | Bloch               |
| Co\textsubscript{0.2}Zn\textsubscript{0.8}Mn\textsubscript{4} | P4\textsubscript{1}32 (NC)                             | 318          | 120                       | Bloch               |
| Fe\textsubscript{2}Co\textsubscript{1–x}Rh\textsubscript{3}Mo\textsubscript{3}N \textsuperscript{75} | P4\textsubscript{1}32 (NC)                             | \( \sim 115 \) | \( \sim 110 \)           | Bloch               |
| Fe\textsubscript{3}Sn\textsubscript{2} \textsuperscript{76}         | R-3m (C)                                                | 630          | 150                       | Bloch (ring-type)   |
| Mn-Ni-Ga alloys\textsuperscript{77} | P6\textsubscript{3}3/mmc (C)                          | \( \sim 350 \) | \( \sim 90 \)             | Type-II bubble      |
| GaV\textsubscript{4}Sn\textsubscript{8} \textsuperscript{73} | R3m (NC)                                                | 12.7         | \( \sim 22 \)             | Neel                |
| Mn\textsubscript{1.4}Pt\textsubscript{0.8}P\textsubscript{1.2}Sn\textsubscript{1} \textsuperscript{79} | I-42m (NC)                                             | \( \sim 400 \) | \( \sim 150 \)           | Antiskyrmion        |

\textsuperscript{A} Material NC = noncentrosymmetric.
After the theoretical understanding of the role atomic arrangement in a crystal lattice and various spin interactions play in the stability of noncollinear spin textures in these materials, development of different detection techniques has proven to be instrumental in their experimental discovery.

III. EVOLUTION OF DETECTION TECHNIQUES OF MAGNETIC SKYRMIONS IN B20 MATERIALS

The experimental discovery of skyrmions has led to the exploration of skyrmion hosting materials and techniques to detect the skyrmion phase. Development of instrumentation to observe skyrmions is a key aspect which led the skyrmion research to flourish in the basic sciences. In this section, we discuss the common skyrmion detection techniques on well-known skyrmion hosting B20 materials.

A. Reciprocal space detection of magnetic skyrmions in bulk crystals

As previously mentioned, magnetic skyrmions were first experimentally discovered in a 1 mm single crystal of MnSi using SANS. Since this initial discovery, SANS has been used to positively identify magnetic skyrmion lattices in a number of different cubic B20 magnetic materials including FeGe, MnGe, and Fe$_x$Co$_{1-x}$Si. This technique is commonly used to analyze bulk crystals and more recently thin film samples. In most B20 materials, upon application of a small applied field ($\sim 0.1$ T), the helimagnetic spin state rotates to align its periodic wave vector, $Q$, along the axis of the applied magnetic field resulting in the formation of the conical state. At temperatures just below $T_c$, there exists a small window of the applied magnetic field where the conical state will transform into a skyrmion lattice shown in the magnetic phase diagram in Fig. 1(e). Both the conical and helimagnetic states are known as single $Q$ states since only one wave vector is required to describe their periodicity. In a SANS experiment, the transition from the helimagnetic to the conical state is typically inferred from the disappearance of the diffraction spots associated with the helimagnetic phase since the periodicity of the conical state is in the direction of the incident beam. The emergence of the skyrmion phase as a function of temperature for any random orientations of the applied magnetic field characterized by the observation of six Bragg reflections on a regular hexagon is strictly perpendicular to the magnetic field [Fig. 1(d)]. The skyrmion lattice is described as a triple $Q$ state since three wave vectors are now required to describe the packing of the skyrmion lattice state. Increasing the applied magnetic field results in a re-emergence of the conical state from the skyrmion lattice phase, which will then finally transform into a fully field polarized state. SANS has proven to be a powerful tool to study the complex magnetism intrinsic to these skyrmion hosting materials. However, the large crystal size required for SANS experiments makes studying confined systems such as thin films exceedingly difficult, or impossible in the case of single nanostructures.

A surface sensitive technique known as resonant elastic X-ray scattering (REXS) unambiguously identifies the helical, conical, and skyrmion lattice states in various B20 compounds and combines element-selectivity with extremely fast time resolution.

When probing a skyrmion lattice, X-rays acquire the momentum transferred directly from the periodicities of the long-range magnetic order of spin structures. Therefore, the scattering form factors for the helical and skyrmion orders are significantly different in REXS, unlike the case in SANS, where they are almost the same. This makes REXS a powerful technique that can uniquely identify the skyrmion structure as compared to SANS. Typical REXS data of different magnetic phases in a single crystal are obtained from scattering of incident polarized soft X-rays scattered from the samples and collected using a CCD camera to produce reciprocal space maps (RSMs). However, it is a surface-sensitive technique that requires high quality single crystals with well-defined and smooth facets to increase the signal to noise ratio of scattered X-ray with magnetic phase information.

B. Magnetic susceptibility and spectroscopy detection of skyrmions

Almost all magnetic materials are thoroughly studied through magnetization and magnetic susceptibility measurements, and skyrmion hosting materials are no exception. Direct current (DC) magnetization measurements are used to determine the $T_c$ and saturation magnetization of these weakly ferromagnetic materials. However, DC techniques yield little information about the skyrmion phase. To probe the skyrmion phase, alternating current magnetic susceptibility (ACMS) experiments are necessary. Previous field sweep studies in several skyrmion materials, including MnSi, Fe$_x$Co$_{1-x}$Si, and MnGe, have revealed a distinct broad dip in magnetization curves at critical fields related to the formation and destruction of the skyrmion lattice, or the so-called “A-phase” in reports before magnetic skyrmions were understood. For instance, ACMS experiments were carried out for the Fe$_{0.95}$Co$_{0.05}$Ge system ($T_c \sim 276$ K) at a low excitation amplitude of 0.1 mT and an excitation frequency of 10 Hz to reveal the stability of the skyrmion phase, where the AC moment is plotted as a function of applied magnetic field as shown in Fig. 4(a). For all temperatures below $T_c$, an increased value of the AC moment was observed for magnetic fields between $\sim 250$ Oe and $\sim 450$ Oe. The two inflection points of this broad dip reveal and mark the formation and the destruction of the skyrmion lattice in Fe$_{0.95}$Co$_{0.05}$Ge as $H_B$ and $H_{A2}$, respectively. Upon destruction of the skyrmion lattice, these skyrmion materials are known to return to the conical state before finally transitioning into the fully field polarized state or ferromagnetic state. These magnetic measurements are useful not only for indirectly probing the skyrmion phase stability regime [Fig. 4(b)] but also for understanding all of the complex magnetic states inherent to skyrmion materials which could be critical for determining how skyrmion phases interact with other magnetic states.

ACMS measurements could help us to determine the stability regime of the skyrmion phase in bulk crystals; however, the signals are not unique to skyrmion phases. In contrast, recently, microwave absorption spectroscopy (MAS) has been used as a powerful tool for identifying and studying the spin dynamics in skyrmion hosting materials as it provides a specific resonance response associated with all magnetic phases (field polarized, conical, helical, and...
skyrnion phases). The combination of MAS, micromagnetic simulations, and analytical theory has been used to identify the various magnetic phases associated with cubic B20 materials such as FeGe, MnSi, Fe_{1-x}Co_{x}Si, and Cu_{2}OSeO_{3}. For example, the electrical broadband spectra were calculated with the MAS measurement device setup with a disc shaped sample of MnSi [Figs. 4(c)–4(f)], where the relative amplitude of the scattering parameter is plotted with absolute frequency. The spectra are dominated by a broad minimum that is accompanied by weaker signals where the skyrmion phase is predicted to be stable (marked by arrows). The magnetic resonances of the skyrmion lattice phase and other magnetic phases have been simulated and quantitatively identified with a varying applied magnetic field in MAS measurements. The resonances consist of a clockwise and an anticlockwise gyration mode of the skyrmion cores, as well as of a single breathing mode which are plotted with respect to the varying applied field [Fig. 4(g)] and compared with theoretical studies [Fig. 4(h)]. The characteristic changes in the spectra coincide with the magnetic phase boundaries determined for the same samples from ACMS measurements.

C. Real space observation of magnetic skyrmions

To overcome the sample size limitations using techniques discussed in the section above and to provide real space visualization of these exotic spin textures, different types of magnetic contrast imaging techniques have been utilized to study the skyrmion phase, especially in nanostructures, including Lorentz transmission electron microscopy (LTEM), electron holography (EH), and magnetic force microscopy (MFM). By far, the most popular imaging technique is LTEM due to its relative ease of use and high sample throughput. LTEM of the Fe_{0.5}Co_{0.5}Si thin film was the first example for real-space observation of the magnetic skyrmion lattice [Fig. 1(f)]. In situ observation of the magnetic constant is performed with the sample in a field-free region in the TEM column by turning off the main objective lens and using another lens known as the Lorentz lens placed below the sample as the imaging lens. The resolution of the LTEM is significantly lower (~2 to 5 nm) because of this objective lens modification compared to traditional TEM techniques, but for many magnetic spin structures, such as skyrmions, this resolution is sufficient. For example, the real space
observation of the cubic skyrmion lattice in a helimagnet MnGe with a periodicity of ~3 nm has been successfully imaged with LTEM imaging.\textsuperscript{13} The magnetic contrast is seen only in over- and under-focused images [Figs. 5(a)–5(c)], and it is produced by the Lorentz force of the in-plane magnetization of the sample. The magnetic contrast of skyrmions appears as circular spots, as shown in the case of an FeGe NW [Fig. 5(d)].\textsuperscript{12}

The LTEM technique not only provides information regarding the spin texture of the skyrmion but also enables the observation of the nucleation and fusion processes and the distortion of skyrmions with the varying applied magnetic field and temperature. Adjusting the temperature and magnetic field in the LTEM allowed for the mapping of the magnetic phase diagram, for example, as shown in the case of the Fe\textsubscript{0.97}Co\textsubscript{0.03}Ge nanoplate [Fig. 5(e)].\textsuperscript{44} The helimagnetic phase generates a helical stripe pattern [Fig. 5(f)] and the skyrmion lattice appears as hexagonally arranged spots [Fig. 5(g)] across the whole Fe\textsubscript{0.97}Co\textsubscript{0.03}Ge nanoplate.\textsuperscript{44} The real space observation of skyrmions via LTEM serves as an important piece of evidence for supporting skyrmion detection from magnetotransport measurements.\textsuperscript{38,44} Similar experiments have been used to map out the magnetic phase diagrams of several skyrmion hosting materials with the cubic B20 nanostructures.\textsuperscript{2}

While LTEM has become a ubiquitous technique for studying magnetic skyrmions in real space, it has some limitations that can be overcome using a more in-depth and time intensive microscopy technique known as electron holography (EH).\textsuperscript{101–104} One of the major drawbacks of LTEM is that the magnetic contrast can be imaged at over- and underfocused TEM mode due to magnetic induction between the electron beam and in-plane magnetic components of the target magnets, leading to Fresnel fringes obscuring all magnetic contrast near the edges of the sample.\textsuperscript{105} In thin films and nanostructures, these fringes can potentially blur the entire area of interest especially when the size of the nanostructure approaches the sub-100 nm length scale. In contrast, the EH technique uses in-focus imaging to produce a magnetic contrast, overcoming this issue. During the experiment, the incident electron beam is split via a biprism into two beams: one travels through the sample (sample beam) and

**FIG. 5.** Real space observation of the magnetic skyrmion in B20 nanostructures using LTEM and EH. LTEM observation of the B20 FeGe NW shows no magnetic contrast in the zero magnetic field for (a) in-focus, however, (b) overfocused, and (c) underfocused LTEM images of the NW with the zero magnetic field, showing the striped magnetic contrast corresponding to the helical phase. (d) LTEM images of an FeGe NW obtained at 95 K shows a skyrmion chain state desired for racetrack memory application. (e) Magnetic phase diagram of Fe\textsubscript{0.97}Co\textsubscript{0.03}Ge nanoplates mapped using three different detection techniques, which supports the LTEM observation of (f) helimagnetic and (g) skyrmion lattice phase formation. Real space observation of the skyrmion spin texture via electron holography conducted on a Fe\textsubscript{0.5}Co\textsubscript{0.5}Si thin film shows (h) the surface plot of the absolute phase shift in the vicinity of the skyrmion. (i) Electron phase shifts of the helimagnetic and skyrmion lattice phase as a function of sample thickness (experiments carried out in 300 kV and 1000 kV microscopes) with the schematic inset showing the three-dimensional spin structure of a skyrmion. (j)–(m) Electron holography imaging experiments conducted on a Fe\textsubscript{0.75}Co\textsubscript{0.25}Si NW sample: Magnetic phase contrast images show (j) helimagnetic and (k) skyrmion phases in the Fe\textsubscript{0.75}Co\textsubscript{0.25}Si NW. The skyrmion enclosed in the rectangle in (k) in the forms of (l) its color-coded display (using the color wheel) and (m) the magnetic phase contrast map. The scale bar in (j) and (k) is 50 nm and (l) and (m) is 30 nm. [Panels (a)–(d) are reproduced with permission from Stolt et al., Nano Lett. 17, 508 (2017), Copyright 2017 ACS. Panels (e)–(f) are reproduced with permission from Stolt et al., Adv. Funct. Mater. 29, 1805418 (2019), Copyright 2019 Wiley-VCH. Panels (h) and (i) are reproduced with permission from Park et al., Nat. Nanotechnol. 9, 337 (2014), Copyright 2015 Springer Nature Limited. Panels (j)–(m) are reproduced with permission from Mathur et al., ACS Nano 13, 7833 (2019), Copyright 2019 ACS.]
the other travels through the vacuum (reference beam). At the detector, the two beams converge and produce an interference pattern (a hologram) that can be used to calculate the phase shift of the sample beam over the entire image. This phase shift includes two separate components: a thickness or mean inner potential (MIP) component and a magnetic component. The MIP phase shift can be easily removed by taking a phase shift image above the magnetic transition temperature, \( T_c \). Above the \( T_c \), the image should contain only the MIP phase shift as the sample is in a paramagnetic state, and this MIP phase shift can be subtracted from all future phase shift images taken below \( T_c \). Removal of the MIP phase shift results in a pure magnetic phase shift image that is sensitive to in-plane magnetization and contains three-dimensional information regarding the skyrmion structure. 

Initially, the EH technique was used on a thin sample of Fe\(_{0.5}\)Co\(_{0.5}\)Si to produce the first real space imaging evidence of skyrmions with quantification of the absolute phase shift associated with the skyrmion spin structure and its vicinity as shown in Fig. 5(b). The linear correlation with the thickness of the thin film sample with the absolute phase shift [Fig. 5(i)] results in image reconstruction of the long tubelike 3D skyrmion structure that exists in cubic B20 materials [Fig. 5(i) inset]. Since then, several other skyrmion materials have been studied with the EH technique, but more importantly, it has been utilized to further understand the details of three-dimensional spin textures in confined systems, including when the skyrmion tubes terminate as a magnetic singularity (see more discussion later in Sec. IV B).

Recently, a one-dimensional skyrmion lattice arrangement was found and imaged in a Fe\(_{0.75}\)Co\(_{0.25}\)Si NW using EH. The helimagnetic stripe pattern [Fig. 5(i)] and skyrmion phase [Fig. 5(k)] are clearly visualized in a NW without performing any mechanical processing (ion milling or deposition of a PtCr layer) or other treatments on the NW. This study demonstrates the technical capability of EH to image a weak-phase object such as a skyrmion even in sub-100 nm sized nanostructures.

**IV. SKYRMIONS IN THE NANOSTRUCTURED GEOMETRY**

As discussed previously, in bulk samples such as large single crystals and polycrystalline powders, magnetic skyrmions exist only in a small pocket of temperature and applied field region just below \( T_c \) of the material. This poses a challenge for the utilization of magnetic skyrmions in proposed magnetic information storage applications, as small variations in temperature or applied magnetic field could cause the destruction of the skyrmion phase. However, it has been shown theoretically that geometrical confinement of the magnetic skyrmion phase in a nanostructure can increase the stability of the skyrmion phase via destabilization of the conical phase. The stabilization of the skyrmions in nanoscale systems was also theoretically predicted by the introduction of large anisotropy energy and experimentally confirmed from skyrmion phase stability in a MnSi NW [Figs. 3(a)–3(c)]. Due to the miniaturization of real memory devices, it is also crucial to understand the stability and electrodynamics of skyrmions in confined geometries. In this section, we highlight the detection of the skyrmion stability regime and current dynamics in single-crystal nanostructures made by bottom-up synthesis and FIB fabricated nanostructures of B20 materials.

**A. Detection of skyrmion stability in the NW morphology using cantilever magnetometry**

In addition to the clear real space observation of the magnetic skyrmion in MnSi NWs and FeGe NWs using LTEM, the experimental mechanism behind skyrmion stabilization for the NW morphology has also been studied in a rather unique way using cantilever magnetometry. Cantilever magnetometry gives insight into the magnetization of a single nanostructure and yields similar results to bulk magnetic susceptibility data albeit with more time intensive data acquisition and processing. Furthermore, this technique...
also enables detection of magnetic phases when the applied magnetic field is parallel to the NW axis which is not possible for previously discussed magnetic contrast imaging. The cantilever magnetometry technique achieves its nanostructure sensitivity by directly bonding the magnetic NW to a nonmagnetic cantilever [Fig. 6(a)] and monitoring the resonance frequency, $f$, of the cantilever as a function of applied field, $\Delta f$, with any change in the magnetization of the NW [Fig. 6(b)]. Dips in the resonance frequency similar to AC susceptibility measurements of a MnSi single crystal can be seen in the region where a skyrmion lattice is expected to exist [Fig. 6(c)]. Using this technique, the skyrmion stability region for the MnSi NW can be mapped out on a magnetic phase diagram and is in good agreement with the LTEM experiments. These experiments were then repeated on MnSi NWs with different aspect ratios to study the potential stability difference caused by shape anisotropy, but the results were inconclusive. Likely, different aspects of a NW play a role in the stabilization of the skyrmion phase such as uniaxial anisotropy due to the NW shape.10

B. Magnetic skyrmions in various nanostructure morphologies

Initial studies of magnetic skyrmions in nanostructures made clear that the nanostructure geometry plays a large role in stabilizing the skyrmion phase. Therefore, much progress has been made in the study of skyrmions in confined geometries, and researchers have

![Image of magnetic skyrmions in various nanostructure morphologies](https://example.com/image.png)

**FIG. 7.** Real space LTEM and EH imaging studies of different nanostructures of the FeGe made by FIB fabrication techniques. (a) LTEM images of FeGe nanoribbons with different widths highlighting the transformation of the skyrmion lattice to a single chain of skyrmions with a varying width at 220 K. (b) Magnetic phase diagram for the nanoribbons of different widths, showing the ability of the thin ribbons to stabilize a single skyrmion chain. (c) EH imaging of an FeGe nanowedge that allows for visualization of change in the magnetic texture with a varying width and magnetic field; scale bar is 150 nm. The skyrmions squeeze to fit in at smaller widths while at larger widths and lower fields, the skyrmions elongate along the width direction. These images also highlight the formation of skyrmions from the helical turns. (d) SEM image and schematic illustration of the fabrication of an FeGe nanodisk using FIB milling. The inset in (d) shows a TEM bright-field image of the cross section of the nanodisk. (e) Magnetic field dependence of the in-plane magnetization of a target skyrmion stabilized in the FeGe nanodisk. (f) The FIB fabricated wedge shaped FeGe structure used for real space visualization of chiral bobbers via EH. (g) Schematic representation of the spin structures for a magnetic chiral bobber and a skyrmion tube. (h) Electron holography image on the wedge shaped FeGe with red arrows indicating weak contrast objects that are identified as chiral bobbers. (i) Phase-shift profiles as a function of position that corresponds to the bands of the same color marked in (h). [Panels (a) and (b) are reproduced with permission from Du et al., Nat. Commun. 6, 8504 (2015), Copyright 2015 Springer Nature Limited. Panel (c) is reproduced with permission from Jin et al., Nat. Commun. 8, 15569 (2017), Copyright 2017 Springer Nature Limited. Panels (d) and (e) are reproduced with permission from Zheng et al., Phys. Rev. Lett. 119, 197205 (2017), Copyright 2017 Americal Physical Society. Panels (f)–(i) are reproduced with permission from Zheng et al., Nat. Nanotechnol. 13, 451 (2018), Copyright 2018 Springer Nature Limited.]
begun studying nanostructures with varying geometrical shapes beyond simple 1D or 2D geometry. Since the skyrmion field is relatively young, the control over nanostructure geometries that can be produced via bottom-up synthesis is limited. The FIB technique has been successfully used to carve out different nanostructured geometries with good control from large crystalline domains of skyrmion hosting materials, despite the low throughput and high cost. FIB deposition of a PtC₆ layer insitu on the surface of the nanostructure has been found to greatly decrease Fresnel fringing allowing for these FIB fabricated nanostructures to be studied more readily with LTEM and EH. ¹⁰⁵⁻¹¹¹ FeGe is by far the most well studied material using these FIB methods, and it was first studied in a FIB fabricated nanoribbon geometry [Figs. 7(a)–7(c)]. ¹⁰⁵⁻¹¹¹ When the width of the nanoribbon was reduced to below two times the skyrmion domain size (a₁₉) of FeGe (∼70 nm), only a single skyrmion chain would form at all temperatures. However, when the width of the nanoribbon was larger than ∼150 nm, the skyrmions would exist as a lattice above ∼200 K, and below 200 K, the skyrmions would exist in distorted skyrmion chains. ¹⁰⁵ This low temperature regime of FeGe is known as the “sparse skyrmion regime” which is unique to nanostructures of FeGe. ¹⁰⁵ This skyrmion phase information is represented in the magnetic phase diagram [Fig. 7(b)] mapped out using LTEM, which shows the control over skyrmion packing with respect to varying width of the FeGe nanoribbon. ¹⁰⁵ Furthermore, a FIB fabricated nanowedge of FeGe was studied using the EH technique to observe the effects of a thickness gradient on skyrmions. ¹¹¹ As shown in Fig. 7(c), skyrmions can form unhindered until the wedge thickness was well below a₁₉. At intermediate thicknesses (∼2 × a₁₉) and lower applied magnetic fields (∼2000 Oe), the skyrmions distort and elongate to fill the gap. Application of a stronger magnetic field (∼3000 Oe) causes the distorted skyrmions to transition into a “zig-zag” skyrmion lattice. Moreover, each single turn of the helix in the helimagnetic state would directly form into the skyrmion upon application of the magnetic field, which is marked by the white arrows in Fig. 7(c). This study yields new insights into the transformation of magnetic spin structures with respect to geometrical confinement of the skyrmion hosting nanostructures.

Increasing confinement of skyrmions from the 1D systems such as the nanoribbons and nanowedges to a pseudo 0D system such as a nanodisk has been theoretically predicted to stabilize the skyrmion phase further. With sufficiently strong confinement, the skyrmions are predicted to become the ground magnetic state of the system as a “target skyrmion,” ¹¹² which gets its name from the two rings of opposite chirality that form a concentric ring “target” without an applied magnetic field. The EH study of FeGe nanodisks with a diameter of 160 nm and thickness of 90 nm [Fig. 7(d)] revealed a target skyrmion (2π-vortex) as a magnetic ground state at 95 K [Fig. 7(e)], which was the first evidence for the confinement induced magnetic skyrmion ground state (60–320 mT). ¹¹²

Moreover, a FIB fabricated nanowedge with well controlled and specific dimensions [Fig. 7(f)] was used to perform real space observation of 3-D spin structures stabilized in the FeGe system known as the chiral bobber (ChB). ¹⁰⁷⁻¹⁰⁹ These ChBs coexist with a regular lattice of skyrmion-tubelike structures in the FeGe system [Fig. 7(g)]. ¹⁰⁷ However, the penetration depth of the spin modulation of chiral bobbles is limited along the direction of the applied field due to the formation of magnetic singularity and occupies a lesser volume in comparison to the lattice of skyrmion tubes. The EH technique proved beneficial to identify ChBs in the vicinity of the skyrmion tube lattice [Fig. 7(h)]. This is possible due to the corresponding weak phase shift of the ChB as compared to the average value from skyrmion spin textures, which is represented as the phase shift profile of the skyrmion and ChB [Fig. 7(i)]. ¹⁷

V. ELECTRICAL DETECTION OF SKYRMIONS AND SKYRMION DYNAMICS IN NANOWIRES

The techniques described above can allow the observation and detection of skyrmions in bulk and/or nanostructures, but none of these methods can be implemented as a practical detection method in information storage devices such as racetrack memory. ¹⁹ They also do not address the interesting electron-skyrmion interactions that are likely to stem from the skyrmion’s nontrivial topology. For these reasons, transport studies are critical for understanding the fundamental electron-skyrmion interactions, as well as for developing a technology that could reliably detect magnetic skyrmions in an information storage device. The implementation of purely electrical detection of the skyrmion is crucial as it reveals the presence/absence of skyrmions which enables the reading process of information in a racetrack memory device architecture. ¹⁰⁸⁻¹¹⁵ Most studies on skyrmions in nanostructures have been primarily carried out using magnetic imaging, while electrical measurements of skyrmion hosting nanostructures is limited.

A. Magnetoresistance (MR) measurement for determination of the skyrmion stability regime

Transport studies of magnetic materials including skyrmion materials usually begin with magnetoresistance (MR) measurements as they are facile to conduct and yield important information about the conduction electron interactions with different magnetic phases. ²⁰⁻²⁸ MR measurements study the change in the electrical resistance as a function of applied magnetic field relative to the zero field [Eq. (2)], allowing for different magnetic phases to be electrically probed,

\[
\text{MR\%} = \frac{R(H) - R(0)}{R(0)} \times 100, \tag{2}
\]

where R(H) and R(0) are the resistances at a specific applied magnetic field and zero field, respectively. For example, in the MR experiments on a MnSi NW [inset of Fig. 8(a)] set up in the parallel configuration, where the direction of the applied magnetic field is parallel to the NW’s long axis, ³⁷ the temperature was swept while applying a constant magnetic field [Fig. 8(a)]. This measurement allows for the identification of the Tc, which is seen as a large dip (∼4%) in the MR signal at ∼32 K (higher than that reported for bulk MnSi, Tc ∼ 28 K). ³⁵⁻³⁶ The spin structure evolution in NWs can be represented by plotting field-driven isotherms (MR-H) by sweeping the applied magnetic field at a constant temperature. For MnSi NWs, the MR results under the parallel configuration do not vary greatly from those under the perpendicular configuration; however, in both cases, a more stabilized skyrmion regime relative to bulk crystals or thin films was observed. ³⁷ This large difference in the signal change between the two configurations is common in magnets with large aspect ratios where the magnet will have an easy and a hard axis of magnetization resulting in an anisotropic MR (AMR) signal. ³⁷ In the case of a magnetic NW, the easy axis is expected
to be along the long axis of the NWs barring any large crystalline effects. AMR gives the MR measurements under parallel configuration a signal boost that can be beneficial for the detection of the different magnetic phases. After determination of $T_c$, isothermal MR experiments can be used to determine the critical fields for each subsequent applied magnetic field induced magnetic transition. As the applied magnetic field along the long axis of NWs increases, small kinks and jumps in the MR signal were observed, denoted as $H_{A1}$ and $H_{A2}$ in Fig. 8(b). $H_{A1}$ appears at the applied magnetic field where the transition from the helimagnetic to the skyrmion phase is expected to take place, while $H_{A2}$ appears at the applied magnetic field where the skyrmion phase was observed to transition into the fully field polarized state. In combination with previous LTEM observations, these critical fields can be assigned to the transitions between each of the magnetic phases. Similarly, Fe$_{1-x}$Co$_x$Si NW devices were studied in a parallel MR configuration to study field driven spin modulation along the NW axis. However, the magnitude of the MR signal for Fe$_{1-x}$Co$_x$Si NWs is an order of magnitude smaller than that of MnSi NWs. Therefore, the apparent MR signature of magnetic state transitions such as kinks in MR-H curves was not discernable as shown in the case of an Fe$_{0.81}$Co$_{0.19}$Si NW [Fig. 8(c)]. However, the second derivative of MR-H curves for temperatures below $T_c$ of Fe$_{0.81}$Co$_{0.19}$Si NWs enabled the further assessment of the critical field for magnetic state transitions.

B. Quantized magnetoresistance transitions of an isolated skyrmion in nanowires

Detection of individual or isolated skyrmions by electrical means is crucial for accessing skyrmions as individual information bits. In B20 materials, the skyrmions tend to form a hexagonal lattice structure; hence, in order to achieve stability of isolated skyrmions, nanostructuring has proven to be beneficial. CVD grown NWs have shown a large variation in the diameter, which makes the parallel configuration of the MR experiments on MnSi NWs

![FIG. 8. Magnetotransport measurements on NWs of B20 skyrmion hosting materials. Magnetoresistance (MR) of a 400 nm diameter MnSi NW [inset of (a)] in a parallel configuration. (a) Constant applied field MR measurements with a sweeping temperature highlight the helimagnetic transition. (b) Isothermal MR field sweeps that are used to identify the magnetic transition critical fields. (c) Offset MR-H isotherms between 10 and 36 K of an Fe$_{0.81}$Co$_{0.19}$Si NW in a parallel configuration. (d) Second order derivatives of the MR-H isotherms in panel (c) more clearly reveal the critical magnetic state transitions. The black arrows (H$_{C1}$) and red arrows (H$_{C2}$) highlight the critical fields for the magnetic state transitions at different temperatures. Values for increasing and decreasing field strengths are denoted by the superscripts “+” and “−”, respectively. (e) The observed quantized transitions of MR of a MnSi NW with a diameter of ∼40 nm, and (f) the corresponding illustration of the calculated spin states of the various skyrmion cluster states. [Panels (a) and (b) are reproduced with permission from Du et al., Nano Lett. 14, 2026 (2014), Copyright 2014 ACS. Panels (c) and (d) are reproduced with permission from Mathur et al., ACS Nano 13, 7833 (2019), Copyright 2019 ACS. Panels (e) and (f) are reproduced with permission from Du et al., Nat. Commun. 6, 7637 (2015), Copyright 2015 Springer Nature Limited.]

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advantageous for probing a small number (<10) of skyrmions at a time easily. In a MnSi NW sample [Figs. 3(d)–3(f)], below $T_\text{c} \sim 32$ K, skyrmions were found to exist with a domain size that is roughly 17 nm. Therefore, a NW with a diameter of 40 nm should only host roughly 2 skyrmions of opposite chirality, and these skyrmion 3D tubes run along the long axis of the NW on both sides of the merohedral twinning boundary that runs through the length of the NW. Figure 8(e) shows the magnetic field-driven cascading quantized transitions of skyrmion cluster states in this 40 nm MnSi NW using refined magneto-transport measurements. By tracking the size dependence on the number of quantized jumps in MR-H curves of the skyrmions assembled into cluster states, the stability of the number of skyrmions can be tuned solely with the applied magnetic field, which was also corroborated by the Monte Carlo simulations [Fig. 8(f)]. These studies clearly demonstrate that skyrmions can exist in discrete numbers from single to several skyrmions, and simple MR measurement can enable an electric reading of the number of skyrmions in the cluster states. It is feasible to acquire real space images of the magnetic spin texture in the in-plane applied magnetic field using techniques such as scanning transmission X-ray microscopy and X-ray holography since the probing particles are unperturbed by magnetic fields, in contrast to LTEM and EH measurements. However, further development in these techniques is required to conduct experiments on a NW morphology at cryogenic temperatures. While fundamentally interesting, these MR measurements are not directly applicable to racetrack memory devices as these tubular skyrmions cannot be moved along the long axis of the NW.

C. Topological hall effect detection and skyrmions dynamics in B20 nanostructures

While the MR measurements proved effective for identifying the critical fields for magnetic phase transitions, the measurements cannot reveal anything else about the skyrmion state and do not uniquely confirm the skyrmion phase. Understanding the skyrmion time-dependent dynamics is also needed to track or predict the positions of skyrmions along a racetrack device. An imaging technique such as LTEM has been used to observe skyrmion motion under applied current. However, the experimental apparatus is very complicated and costly, and it is nearly impossible to observe short-time dynamics due to the image blurring. One of the prominent characteristics of the skyrmion spin structure is its emergent magnetic field. This is because when a conduction electron passes through a topologically nontrivial spin texture, the spin of the conduction electron adiabatically couples to the local spins and acquires a quantum-mechanical Berry phase that can be reformulated in terms of an effective magnetic field, which deflects the conduction electrons perpendicular to the current direction [Fig. 2(b)]. The manifestation of this emergent magnetic field is known as the topological Hall effect (THE), which is known as an electronic signature of the skyrmion which can be measured in a Hall device setup [Fig. 9(a)]. The total Hall signal comprises three parts [Eq. (3)] that will each individually add to the total signal, $\rho_{\text{THE}}$: (1) the normal Hall effect (NHE) [Eq. (4)], (2) the anomalous Hall effect (AHE) [Eq. (5)], and (3) the THE, where $\mu_0$ stands for vacuum permeability, $R_0$ is the normal Hall coefficient, $M$ is the magnetization of the sample, and $H$ is the applied magnetic field.

The linear dependence of $\rho_{\text{AHE}}$ on magnetization ($M$) is convenient for the fitting process that can be used to extract the THE signal. For example, in the case of FeGe thin films, the AHE can be effectively calculated and removed in conjunction with magnetization measurements. However, for nanostructure samples, such as MnSi NWs and Fe$_{1-x}$Co$_x$Ge nanolayers [Fig. 9(a)], the magnetization cannot be measured easily. This means that the magnetization and therefore the AHE are assumed to act similar to the bulk MnSi and Fe$_{1-x}$Co$_x$Ge systems. For the Fe$_{0.97}$Co$_{0.03}$Ge nanolayer example, to effectively remove the AHE contribution from the total Hall signal, a fitting and subtraction method was employed by assuming that the AHE behaves as a smoothly varying linear function. Fitting the linear function to the data above the critical field and subtracting the fit across the whole asymmetric component of the Hall signal yield the deviation from a smoothly varying function. As previously stated, the AHE and NHE signals should be smoothly varying, and therefore, any deviation can be accurately described as the THE signal. The extraction process can then be reproducibly carried out on the measurements at various temperatures [Fig. 9(c)]. Plotting the THE signal as a function of temperature and applied magnetic field as a heat map [Fig. 9(d)] creates a form of a magnetic phase diagram that represents the region in which the skyrmion phase is stable in the Fe$_{0.97}$Co$_{0.03}$Ge nanolayer.

Once the THE signal, and therefore the skyrmion phase, has been positively identified (which can be further corroborated with real space imaging as discussed in Sec. III C), the current dynamics of the skyrmion phase can be studied. The THE signal, which is unique to the skyrmion phase, is dependent on several factors, including the skyrmion domain size ($a_{sk}$), the normal Hall coefficient, as well as the skyrmion lattice packing [Eq. (6)].

$$\rho_{\text{THE}} = n \times P \times R_0 \times B_{\text{eff}},$$

where $n$ is the skyrmion packing density, $P$ is the spin polarization of charge carriers, and $B_{\text{eff}}$ is the emergent magnetic field associated with one skyrmion. In addition, the magnitude of the THE signal is also affected by the motion of the skyrmion and its drift velocity. Both SANS and magnetic imaging experiments have shown that skyrmions will begin to move under small applied currents ($\sim 1 \times 10^{-6}$ A/m$^2$) in a B20 skyrmion hosting material through a spin transfer torque mechanism [Fig. 2(b)]. Once the skyrmions begin to depin from the lattice and translate, the effective magnetic field, $B_{\text{eff}}$, that is responsible for the THE will begin to produce an emergent electric field, $E_{\text{eff}}$, through Faraday’s law of induction. This $E_{\text{eff}}$ is oriented opposite to the electric field produced by the electrons deflected due to the THE, which results in a decrease in the THE signal as the skyrmions move. As the current is increased further, the skyrmion velocity increases, so does the $E_{\text{eff}}$ resulting in an ever diminishing THE signal. For this reason, current density dependent Hall effect measurements should give insight into the dynamics of the skyrmion phase and allow for the

$$\rho_{\text{xy}} = \rho_{\text{NHE}} + \rho_{\text{AHE}} + \rho_{\text{THE}},$$

$$\rho_{\text{NHE}} = R_0 \mu_0 H,$$

$$\rho_{\text{AHE}} = \left[ \alpha \rho_{\text{xx}} + \beta_0 \rho_{\text{xx}} + \beta_2 \rho_{\text{xx}}^2 \right] \mu_0 M(H).$$
current density dependent drift velocity, \(v_d\), of the skyrmions to be calculated.

The observation of the reduced THE signal due to the emergent field of moving skyrmions was first made on a single crystal of MnSi\textsuperscript{23} and then on the MnSi NW in the perpendicular configuration [inset of Fig. 9(e)].\textsuperscript{53} However, the fabrication of Hall devices on a single NW is much more challenging than those on thin films and nanoplate morphology.\textsuperscript{123,124} In Fig. 9(e), a decay in the THE signal of the MnSi NW was observed with increasing current density. This maximum THE signal at each current density can be determined and plotted [Fig. 9(f)]. Fitting this decay data to an exponential function [Fig. 9(g)] allows for the current density dependent \(v_d\) of the skyrmion phase to be determined, and extrapolation of the \(v_d\) to 0 estimates the critical current density, \(j_c\).\textsuperscript{53} This is the current density required for the skyrmions to depin and to begin to translate. In the case of MnSi NWs, the \(j_c\) was found to be \(\sim 4 \times 10^7\) A/m\textsuperscript{2}, which is roughly 1 order of magnitude higher than that found in the bulk crystals of MnSi (\(\sim 2 \times 10^6\) A/m\textsuperscript{2}).\textsuperscript{53} In comparison to MnSi bulk crystals, the skyrmions are stabilized and moved in the NWs over a much larger temperature and field window, in which they are not expected to be stable in bulk.

Similar Hall measurements have been implemented to FIB fabricated FeGe nanostrips that successfully acquired the quantized THE signal from a cluster of individual skyrmions.\textsuperscript{125} These THE measurements are important for understanding the electrical dynamics of the skyrmion phase, but the overall signals are quite small (10s of nΩ cm) and the THE measurements are quite challenging. In most cases, the THE signal is less than 10% of the total Hall signal and depends on skyrmion size, \(\rho_{yx} \propto B_{\text{eff}} \propto 1/a_{sk}^2\). For reliable electrical detection of the skyrmion phase via THE, fabrication of Hall devices with a high signal-to-noise ratio is crucial. The total THE signal is expected to decrease at higher temperatures with the reduction of spin polarization of materials at elevated temperatures.\textsuperscript{44,120} For low temperature measurements, design of a novel Hall-bar NW device configuration could be beneficial for creation and the THE detection of “metastable” skyrmions by all electrical means.\textsuperscript{126–128} Furthermore, reducing the skyrmion domain size via chemical alloying could lead to a larger THE signal. The future of skyrmion-based memory devices demands more and better selective and sensitive detection techniques for skyrmions in magnetic materials.

VI. SUMMARY AND OUTLOOK

Nanostructures of noncentrosymmetric B20 materials have enabled the studies and exploration of magnetic skyrmions in confined magnetic materials which have shed new scientific insights into the confinement and evolution of magnetic skyrmions and laid a solid foundation for skyrmion-based memory and information technology. An overview of the discovery of the magnetic

FIG. 9. Skyrmion detection and electrodynamics via THE measurements of nanostructures. (a) SEM image of a Fe\textsubscript{0.97}Co\textsubscript{0.03}Ge nanoplate with metal contacts fabricated as a Hall device setup shown in the schematic in panel (b). (c) Extracted THE signal of the Fe\textsubscript{0.97}Co\textsubscript{0.03}Ge nanoplate obtained from isothermal field sweeps at various temperatures with the corresponding (d) heat map representation of the extracted THE resistivity as a function of the temperature and magnetic field. (e) Extracted THE signal obtained from the Hall device fabricated on a MnSi NW as a function of current density that can be fitted as an exponential function to estimate the skyrmion drift velocity, \(v_d\). (f) Maximum THE signal obtained from a MnSi NW as a function of current density that can be fitted as an exponential function to estimate the skyrmion drift velocity, \(v_d\). (g) Skyrmion drift velocity as a function of current density in a MnSi NW. Extrapolation of a linear fit allows for the estimation of the critical current density, \(j_c\), required for skyrmion motion in MnSi NWs. [Panels (a), (c), and (d) are reproduced with permission from Stolt et al., Adv. Funct. Mater. 29, 1805418 (2019), Copyright 2019 Wiley-VCH. Panels (b), (e), and (f) are reproduced with permission from Liang et al., Nat. Commun. 6, 8217 (2015), Copyright 2015 Springer Nature Limited.]
skyrnion as well as the experimental methods used to detect these exotic magnetic textures in noncentrosymmetric materials either in bulk or as nanostructures is presented in this research update. Significant progress in the field of skyrmion research has led to the determination of enhanced stability, electrical detection, and current-driven dynamics of skyrmions, especially in nanostructures of metal silicides and germainides with the B20 crystal structure, using several measurement techniques as discussed herein. These detection methods are discussed in a way that illustrates how each technique can study the magnetic skyrmions with its strengths and weaknesses. Developing more sensitive and accurate methods, especially those methods purely based on electrical transport measurements, to reliably detect skyrmions (including isolated skyrmions) is critical for the realization of skyrmion-based memory devices. Recently, tunneling anisotropic magnetoresistance (TAMR) signal to probe skyrmion domains was acquired via scanning tunneling microscopy. This detection technique may be further extended to giant magnetoresistance (GMR) like device design for skyrmion detection, similar to reading elements in the HDD for ferromagnetic domains.18-23 Visualizing the fine details of the internal spin structures of skyrmions with a novel high resolution magnetic imaging technique such as 4D Lorentz scanning transmission electron microscopy (STEM) could be helpful for further understanding the dynamics of skyrmion motion and their detection.23 As always, discovery of new materials that can host skyrmions at room temperatures and a wider magnetic field range could facilitate the eventual applications of skyrmions, even though this challenge is not unique to nanostructures of skyrmion hosting materials. Apart from the magnetic skyrmion stability in noncentrosymmetric B20 materials, recent observation of chiral fermions in B20 materials stems out curiosity toward understanding of unique topological quantum properties in this class of materials and their implementation in electronic devices.135-138 The development of purely electrical detection techniques to detect skyrmions would lay the groundwork for the utilizing nanostructures of these B20 noncentrosymmetric nanostructures as prototypes for the implementation in next generation spintronic devices.

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