Confinement of Skyrmions in Nanoscale FeGe Device Structures

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Abstract

Skyrmion-containing devices have been proposed as a promising solution for low energy data storage. These devices include racetrack or logic structures and require skyrmions to be confined in regions with dimensions comparable to the size of a single skyrmion. Here we examine Bloch skyrmions in FeGe device shapes using Lorentz transmission electron microscopy (LTEM) to reveal the consequences of skyrmion confinement in a device structure. Dumbbell-shaped devices were created by focused ion beam (FIB) milling to provide regions where single skyrmions are confined adjacent to areas containing a skyrmion lattice. Simple block shapes of equivalent dimensions were prepared within the specimen to allow a direct comparison with skyrmion formation in a less complex, yet still confined, device geometry. The impact of the application of an applied external field and varying the temperature on skyrmion formation within the shapes was examined and this revealed that it is not just confinement within a small device structure that controls the position and number of skyrmions, but that a complex device geometry changes the skyrmion behaviour, including allowing formation of skyrmions at lower applied magnetic fields than in simple shapes. This could allow experimental methods to be developed to control the positioning and number of skyrmions within device shapes.

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Magnetic Bloch skyrmions are localised magnetic configurations with an integer, non-zero topological charge. They resemble magnetic vortices and typically have diameters of a few tens of nanometres. Skyrmions were discovered experimentally in 2009 [1] and since then there have been many suggestions for how they could be used in spintronic devices (reviewed in refs. [2–7]). Proposed devices include racetrack memories [8, 12], logic devices [13, 14], skyrmion transitors [15], nanometre-sized spin transfer oscillators [16, 17] as well as devices for probabilistic [18, 19], reservoir [20] and neuromorphic [21–23] computing. All of these devices (apart from the reservoir computer) require the skyrmions to be confined in a narrow track with a width a few times the skyrmion diameter. In the case of the logic devices and some schemes for the generation and annihilation of skyrmions [24, 25], the skyrmions must be driven through constrictions narrower than the width of a single skyrmion. Some of these devices use interfacial Dzyalohsinskii-Moriya (DM) interactions to form skyrmions in thin films, others use bulk DM interactions in confined geometries. The operation of these devices has been simulated but, with the exception of the skyrmion reshuffler [19], has not been investigated experimentally.

In order to create a reliable, reproducible skyrmion device, we must first understand the factors which control the position, number, and size of skyrmions within a material. Devices such as racetrack memories [2] and discrete geometrical shapes have been studied including discs [26], wedges [27] and triangles [28, 29]. These geometries confine the skyrmions and reveal the impact of physical confinement of skyrmions which is key to the development of potential device shapes. However, to date, the control of individual skyrmions within a device structure is one factor that has limited the development of reliable skyrmionic data storage and retrieval [4]. Geometrical confinement is known to increase the range of temperature and magnetic field over which skyrmions can occur [30, 31]. Figure 1(a) shows the phase diagram of bulk FeGe derived from AC susceptibility measurements and is typical of skyrmion materials. Figure 1(b) is an equivalent phase diagram for a 200 nm thick lamella of FeGe (derived from magnetic x-ray diffraction measurements [32]) where it can be observed that the skyrmion ‘pocket’ has been greatly enlarged. This increased range of stability is well known and is related to the modification of the magnetic structure imposed by the specimen surfaces known as ‘surface twists’ [33].

Electron microscopy of FeGe confined skyrmion device shapes

In this paper we use Lorentz transmission electron microscopy (LTEM) to examine
dumbbell-shaped FeGe elements, all cut from a single crystal, which confine skyrmions to small regions, including a central constriction with a width comparable to the skyrmion diameter (70 nm in FeGe). This forms the type of junction that would need to be used in a skyrmion logic device [14] or for skyrmion creation and annihilation [25]. Focussed ion beam (FIB) milling was used to cut discrete elements from a single crystal of FeGe as shown in Figure 1(c). A thin membrane containing these elements was prepared in cross-section and comprises three dumbbell-shaped elements (D1, D2 and D3). These dumbbells are separated by approximately rectangular blocks (B1 and B2) to allow comparison of the two shapes and examine the impact of the dumbbell-shape on skyrmion formation. The device shapes were coated with platinum which was electron beam deposited to connect and protect them during sample preparation (as shown in Figure 1(d)). Ultimately, a device of this, or a similar design, may allow the movement of skyrmions to be controlled by ‘squeezing’ the skyrmion through the constriction using an applied electrical current or magnetic field gradient [24, 34], with the prospect of allowing control of the speed and number of skyrmions within different areas of a device structure.

When imaged at 90 K in a field-free condition, the helical phase was observed to fill all of the device shapes. Using the transport of intensity equation (TIE)[35], the in-plane magnetic flux density in the device shapes was reconstructed and is shown in Figure 1(e). The TIE reconstruction reveals that, despite confinement, the elements retain their expected magnetic properties and the helical phase persists even in the narrow constrictions, where the wave-vector \( \mathbf{q} \) is always observed to run parallel to the edges of the central constrictions.

At 262 K in an applied magnetic field of 136 mT skyrmions formed in all of the device shapes, as expected from the phase diagram shown in Figure 1(b). Figure 1(f) shows a colour map of the TIE-reconstructed in-plane magnetic flux density. In the block shapes (B1 and B2), the skyrmions form an approximately hexagonal lattice aligned with the longer axis of the shape, but with elongated space-filling of skyrmions where confinement restricts the number of skyrmions that can fit in the device (as labelled in B1). We can see in Figure 1(f) that the dumbbells are not filled with a regular close-packed hexagonal arrangement of skyrmions as observed in the blocks and in larger FeGe samples [30]. In dumbbells D1 and D2, the skyrmions in the smaller ends to the right of the constrictions form an approximately square-lattice arrangement whereas in the larger dumbbell ends the arrangement is closer to hexagonal, as shown in red. In D3, the smallest of the dumbbells, the arrangement of
Skyrmions is best described as ‘space-filling’ as confinement does not allow the formation of more than two skyrmions along the top and bottom edges of the dumbbell ends, and arrangements with an irregular 5-fold coordination can be seen, one of which is outlined in red. These observations indicate that skyrmions in the confined shapes near the Curie temperature use irregular particle-like packing arrangements, filling and adapting to the space available rather than forming regular hexagonal lattices. This includes within the narrow constrictions in the dumbbell shapes where skyrmions form but are distorted, particularly in D1 and D2 where the narrow regions are slightly larger than the constriction in D3.

LTEM images were subsequently acquired at 90 K, 219 K and 245 K. At each temperature an out-of-plane magnetic field was cycled through a hysteresis loop starting from a field-free condition to $-313 \, \text{mT}$ and then to $+310 \, \text{mT}$ before returning to 0 mT, in steps of approximately 30 mT. The objective lens of the microscope was used to apply an out-of-plane magnetic field but the defocus was adjusted to the same value for all images in the hysteresis loop after each change in applied magnetic field. The specimen was heated above the Curie temperature after the 90 K series and before the 219 K and 245 K series were acquired, but not between acquisition of the 219 K and 245 K series. The changes in applied magnetic field give rise to subtle tilts of the electron beam causing diffraction contrast to move across the image so that some of the shapes appear dark in some of the images.

Whilst the blocks and dumbbells were cut from single crystal FeGe, the weaker Pt layer surrounding the isolated shapes creates a subtle orientation variation between the shapes, and the resulting diffraction contrast cannot be minimised in all of the shapes. This diffraction contrast is visible in the bright field LTEM image in Figure 1(d) where some of the shapes appear brighter and some appear darker despite the uniform illumination. Further information on the image processing used to reduce the impact of diffraction contrast on the observed magnetic contrast can be found in the Methods section.

Figure 2 shows the helical phase formed in B1 and D3 under zero magnetic field before and after the specimen was subjected to an applied external magnetic field of 313 mT for the experimental data and 800 mT in corresponding micromagnetic simulations. (Further details on the micromagnetic simulations are in the Methods section). Within the simple blocks, the magnetic helices form the same pattern irrespective of temperature before the external field was applied, with a single wave-vector $\mathbf{q}$ aligned along [100], as expected from previous low temperature measurements [37]. At higher temperatures (219 K and 245 K)
the wave-vector alignment along [100] orientation does not change after the application of an external magnetic field. However, at 90 K the helices are observed to form more complex magnetic structures composed of domains with a constant wave-vector (as shown by the coloured regions overlaid on 90 K data in Figure 2) where the direction of the wave-vector changes abruptly from one domain to the next as the external magnetic field is cycled. A more complex magnetic structure is observed at all temperatures in the dumbbell shapes than in the simple blocks. It is particularly interesting to note that the helical wave-vector runs parallel to the edges (along [111]) in the central constriction in the dumbbell structure at all temperatures, but outside the constriction, the wave-vector rotates. The higher energy configurations (more twisted helices) observed at 90 K in both the blocks and dumbbell shapes are consistent with the micromagnetic simulations indicating that they get stuck in metastable configurations and cannot realign into the lowest energy state. The confined dumbbell geometry is experimentally observed to allow more complex helical states to be stabilised at all temperatures. With a single crystal orientation used for the specimen in this study we cannot deduce whether the alignments of the helical phase wave-vector are controlled predominantly by crystal anisotropy or by geometrical confinement, but through a comparison of the block shapes with the dumbbell shapes we can deduce that a complex device geometry does impact the zero-field micromagnetic alignments present locally in the structure, particularly at temperatures far below the Curie temperature.

To understand the underlying magnetic structure giving rise to the reduced helical contrast observed in the simulations in dumbbell 3, the 3D simulated magnetisation was examined, as shown in Figure 2. Before the field was applied, the system was initialised and relaxed with the wave-vector of the helical phase lying in the plane of the sample. After the magnetic field was applied, the wave-vector of the helical phase can be seen to rotate in some parts of the dumbbell shape to lie out of the sample plane, giving rise to a lower observed contrast in the projected simulations which are used for comparison with the experimental data. This reduced contrast is also observed in some of the shapes in the experimental data (see full data sets in the Supplementary Material). Experimental LTEM only views the projected in-plane component of the magnetic flux density through the entire specimen thickness and cannot separate variations along the beam direction. These are observed as reductions in intensity in the LTEM image (as seen with skyrmion bobbers [38]). The full set of experimental data of all of the blocks and dumbbells is included in the Supplementary
Material and reveals a strong temperature and field dependence on the magnetic structure formed within the shapes.

**Hysteretic behaviour of skyrmion formation in FeGe shapes**

Figure 3 shows a selection of enhanced experimental images (see Methods) from the hysteresis loop acquired for the FeGe shapes B1 and D2 under an applied out of plane magnetic field at 90 K. The phase diagram in Figure 1(b) shows that any skyrmions formed are metastable under these conditions in thinned TEM lamellae. Skyrmions form from helices in two different ways depending on the temperature. At 90 K, each helical rotation shrinks along its length to form a single skyrmion whereas at 219 K and 245 K each helical rotation breaks into a chain of skyrmions (see Figure 4). The skyrmions formed sit close to the edges of the FeGe shapes, including in the constrictions of the dumbbell shapes and rearrange themselves along the edges as the applied magnetic field is increased, spacing out slightly under a 313 mT applied magnetic field. On reduction of the applied magnetic field, the process is reversed but the skyrmions do not move back into their original positions. A single helical rotation nucleates from each skyrmion at its new position, thereby creating a modified helical arrangement in the small devices. The skyrmions form into S-shaped lines within the dumbbell shapes in Figure 3 which inverts when the magnetic field is applied in the opposite direction. This configuration is likely to be formed as a minimisation of energy under the conditions where skyrmions have an attractive force between them, and at low temperature where the skyrmion-edge distance is minimised. The simulated data shows a very close match to the experimental data, following the observed patterns of helices shrinking into single skyrmions, rearranging along the edges of the devices with increasing field and then the re-forming of helical rotations in more complex configurations as a result of the rearrangement of the skyrmions at high field. This is observed for both the block and dumbbell shapes.

Differences are observed between the magnetisation developed in the experimental system and in the micromagnetic simulations in response to an applied magnetic field, even though qualitatively the behaviour is similar. Experimentally, all skyrmions are expelled entirely from the samples at higher temperatures at fields of 350 mT, while in the micromagnetic simulations skyrmions are present up to much higher applied fields, not being entirely expelled even at 800 mT. We believe that this behaviour can be explained by a combination of the effects of thermal variations, edge roughness of the real samples, and anisotropy which...
are not explicitly considered in the simulations.

These results provide an important insight into skyrmion behaviour which is critical for the design of skyrmion devices. The temperature and field history, in combination with device geometry, could be used to predict skyrmion positions and the inter-relationship between helical phase and skyrmion number at low temperature would allow control of skyrmion density within a given device geometry.

Figure 4 shows data from the hysteresis loops at 219 K and 245 K with the selected devices chosen as those least affected by diffraction contrast through the hysteresis loop, in the region of the phase diagram (Figure 1(b)) for thermodynamically stable skyrmion formation. Here we see that, when an external magnetic field is applied, a skyrmion lattice is formed in the device shapes, which partially or completely fills the FeGe shapes. Partial filling of a material with skyrmions is suggested to be due to the thermodynamic energy barrier in a real material. It is seen in larger standard FIB-prepared TEM membranes [41] and therefore is not expected to be as a result of confinement. The skyrmions formed fill (or partially fill) the shapes and as the applied external magnetic field is increased, slowly reduce in number and move away from the edges of the devices. The correlation between helical phase and skyrmion formation is not as well defined as at 90 K and thermodynamic contributions at these higher temperatures encourage the splitting of helical rotations into two or more skyrmions, rather than the pattern of shrinking helices observed at 90 K. These experimental data reveal a dependence of skyrmion formation on device geometry. Within Figure 4 we can observe the first formation of skyrmions in the device shapes as the applied magnetic field is reduced from the field-polarised state to 167 mT at 219 K and to 134 mT at 245 K. Here we can see that skyrmions consistently form first in the dumbbell shapes when transitioning from the field-polarised state, although not always filling the dumbbell shapes entirely. The dumbbell shapes have 1.3 times the edge length to area ratio compared to the block shapes, which reduces the nucleation energy required for skyrmion formation [42], thereby allowing them to form in the complex shapes before the simple shapes. To further quantify this effect, analysis using smaller field steps and varying the rate of temperature change is required. These experimental results indicate that increasing the edge length to area ratio in a chosen device geometry could be used to stabilise skyrmions and reveals that the skyrmion density within a device is dependent on the geometry of the device and not just the temperature and applied magnetic field.
Skyrmion-edge interactions

To determine the equilibrium geometrical confinement parameters for these samples, the skyrmion-edge distance, $d_{se}$, was measured for each device structure (details in Methods). Skyrmions sit at an equilibrium distance of $d_{se} = 73 \pm 5$ nm from the edge in the block shapes and the dumbbell ends for low applied magnetic fields at 245 K (as shown in Figure 5(a)). Within the central constriction in the dumbbells there is insufficient space for them to sit at this distance from the edge. As seen in Figure 5(a), skyrmions do form and sit within the constriction indicating that they can be squeezed into confined spaces. This is again temperature-dependent and it is only at 90 K that a skyrmion is seen at the centre of the constriction, whereas at 219 K and 245 K they sit just to the sides of the narrowest constriction. At 90 K, $d_{se} = 60$ nm but in the constriction, the skyrmion-edge distance is reduced to 47 nm. Increasing either the temperature or the field causes the skyrmions to move away from the FeGe edges, as shown in Figure 5(b) which plots the variation of edge-skyrmion distance, $d_{se}$, as a function of applied field and temperature. This is consistent with predictions by Leonov et al. [43] and experimental data from larger samples by Du et al. [44] where a linear relationship between $d_{se}$ and applied magnetic field was observed, with a trend for increasing $d_{se}$ as the temperature increased, as suggested by Leonov et al. [45].

At 90 K, skyrmions are still present in the narrow constriction until the applied field exceeds a magnitude of 260 mT, whereas at 219 K and 245 K the equivalent fields are much lower at approximately 160 mT and 130 mT. The presence of skyrmions in the narrow region is expected to be dependent on the length and shape of the constriction; here it is short and not parallel-sided. The edge potential appears to act as a barrier to the skyrmions around most of the sample, and as shown in Figure 5, skyrmions move away from edges as the applied field or temperature is increased. However, on detailed examination of the hysteresis loop data acquired at 245 K as the applied field is increased, some individual skyrmions (marked with blue circles) sitting close to the sharp internal corners of the dumbbell shape are observed to behave differently as shown in Figure 5(c) and (d). As the applied field is increased, these marked skyrmions sitting closest to the sharp internal corners are believed to be annihilated through the edge rather than being pushed into the centre, as is observed at all other positions and temperatures in the shapes. This mechanism of annihilation and creation of skyrmions has been proposed and modelled using micromagnetic simulations of a notch [24] and a strip [46] but has not previously been experimentally observed. This
behaviour is only observed at 245 K revealing a thermodynamic dependence to this effect which cannot be modelled in our micromagnetic simulations. This experimental observation confirms the theoretical predictions that sharp notches or corners can create thermodynamic short-cuts for the annihilation of skyrmions, an effect that has not been previously observed at such sharp corners in FIB-prepared samples.

Examining the dumbbell and block shapes as a whole, the sum of skyrmions formed in all of the shapes (B1–2 and D1–3) as a function of field is shown in Figure 6. This reveals a strong dependence on temperature and field direction which could be used to optimise skyrmion formation in the devices. As before, the field loop started at 0 mT, reduced to −310 mT before increasing to 313 mT and then returning to 0 mT. At 245 K, skyrmions are quickly formed as the field strength increases, and retained to higher fields. It is only at 245 K that thermodynamic barriers are overcome and the hysteretic behaviour of skyrmion formation is reduced whereby equal numbers of skyrmions are present in the devices when formed from either the field-polarised (or cone) phase or the helical phase. At 219 K the number of skyrmions formed in the device shapes when forming from the helical phase is approximately twice that formed from the field-polarised phase. At 90 K the field-polarised phase was not reached under the conditions used in these experiments and therefore the skyrmions were only observed forming from the helical phase. If we consider the ideal packing of skyrmions within the device shapes as a close-packed arrangement, the complex structure of the dumbbell shapes would lead to a lower packing density than the simple block shapes as more space is ‘wasted’. However, the preferential formation of skyrmions at edges and the space-filling arrangements observed with the skyrmions enhances the skyrmion formation in the complex dumbbell shapes, and a higher skyrmion density is observed in the dumbbells for all temperatures and fields when compared to the simple block shapes which have a similar volume. This quantifies the effect observed earlier, and confirms that increasing the edge surface area to volume ratio can be used to control skyrmion density.

Conclusions These complex device geometries have revealed a different behaviour of skyrmions compared to that in a simple device geometry. Despite confining the device to a length-scale which only allows a single skyrmion within the constriction, skyrmions were still observed to form in the smallest of spaces. These experimental results indicate the significant impact of edges in enhancing skyrmion formation due to the energy instability present at the edges [42], but the data shows that this is highly temperature and field dependent. The
history of specimen temperature and applied external field was revealed to be important when considering the formation of skyrmion and helical phases. The interdependence of skyrmion and helical phase is critical for an understanding of skyrmion formation within a device, and could be used to control skyrmion number and position. The close match observed between simulated and experimental results at low temperature indicates that simulations could be used effectively to predict any low-temperature skyrmion behaviour in proposed device geometries but experimental verification is still required for temperatures closer to the Curie temperature.

I. METHODS

A. Details of sample synthesis

The FeGe single crystals were grown by the chemical vapour transport method with iodine as the transport agent, as described by Richardson [47]. Magnetometry measurements were performed on the bulk FeGe sample. The Curie temperature of the sample, \(T_C\), defined as the point of greatest slope in the magnetisation, \(M\), was found to be 280.5 K. Isolated individual dumbbell-shaped and block-shaped lamellae were prepared from a single crystal of FeGe using a FEI Helios Nanolab dual-beam. Initially the 30 kV Ga\(^+\) focused ion beam (FIB) was used to prepare a 400 nm thick lamella still attached at the side and bottom within a trench, and then careful patterning of the devices using the FIB was carried out to define the narrow constrictions and separations between the dumbbells and block shapes. Electron beam platinum deposition was used to coat both sides of the patterned devices before lifting out the lamella and mounting on a horizontal Omniprobe grid. The grid was rotated to the vertical position and a cross-section of the devices was prepared 1.8 \(\mu\)m in from the edge to achieve the correct dimensions of the dumbbell constrictions.

B. Electron Microscopy

The thinned cross-section of FeGe device shapes was mounted in a Gatan liquid nitrogen cooled model 636 transmission electron microscope (TEM) holder and examined in an FEI Titan\(^3\) TEM equipped with a Lorentz lens. The specimen was initially mounted in a magnetic field-free condition and a calibrated external magnetic field was applied out of
the plane of the specimen using the objective lens of the TEM. To observe magnetic contrast in the TEM, a phase imaging technique is required, and these are only sensitive to the in-plane components of the magnetic field arising from local magnetisation within the specimen. Bloch skyrmions appear as bright or dark areas of contrast when imaged away from focus, depending on defocus and orientation of applied magnetic field. The helical phase can be characterised using defocused imaging, but the field-polarised and cone phases cannot be distinguished from each other as there is no net in-plane component of magnetic field for either when an out-of-plane magnetic field is applied. Defocused Lorentz TEM (LTEM) image series were acquired at 90 K and 263 K with an applied external magnetic field varying between 0 mT and ±310 mT. Hysteresis experiments were conducted at 90 K, 219 K and 245 K and were imaged using defocused Lorentz TEM. Images were acquired on a 2048 \times 2048 pixel CCD and the defocused Lorentz images were energy filtered using a 10 eV Gatan Tridiem imaging filter. At each change of magnetic field within the hysteresis loop, the LTEM image was refocused before adjusting the defocus to 200 \mu m for each image acquired.

C. Micromagnetic Modelling

The simulations of FeGe geometries of the systems were performed using the software MuMax3 \cite{48}, in order to try to understand the underlying behaviour of these systems, and to investigate how skyrmions form in ‘large’ confined geometries. In order to do so, we start from the micromagnetic energy density functional $\epsilon[m]$ describing a bulk chiral ferromagnet in the absence of any magnetocrystalline anisotropy:

$$\epsilon[m] = A(\nabla m) + D m \cdot (\nabla \times m) - M_s m \cdot (H\hat{e}_z + H_d) \quad (1)$$

where H is an externally applied field in the out-of-plane direction, m is the normalised magnetisation and $H_d$ is the demagnetising field. In these simulations, we use values for FeGe of saturation magnetisation $M_s = 384 \text{ kA m}^{-1}$, exchange stiffness $A = 8.78 \text{ pJ m}^{-1}$, and Dzyaloshinskii-Moriya interaction constant $D = 1.58 \text{ mJ m}^{-2}$ \cite{31}.

The mask generation process for creating the mesh used in the micromagnetic simulations is described in the Supplementary Material. In the simulations, we initialise each of the five
systems with a helical initial state with an in-plane periodicity of \( L = 4\pi A/D \) and the wave-vector \( \mathbf{q} \) aligned along the \( x \)-axis. We choose this initial state because it is close to the observed equilibrium experimental systems at 0 mT far from the Curie temperature. The system is evolved using the steepest descent method \[49\] until a metastable equilibrium is reached, which we consider to be when the change in magnetisation, \( |\Delta \mathbf{m}| \leq 10^{-5} \). We then increase the magnetic field from 0 to 800 mT and then reduce it back to 0 mT, changing field in steps of 2 mT.

D. Image processing

Diffraction contrast occurs in the LTEM when areas of a specimen are tilted close to a strongly diffracting condition, thereby reducing the intensity observed in that area in a bright field image. In a single crystal specimen it can be reduced by tilting the sample a fraction of a degree, but in this device sample, despite being composed of lamellae cut from an oriented single crystal, there is a small bend which makes it difficult to remove the slowly varying strong diffraction contrast across all of the shapes. No tilt adjustments were made during the acquisition of the hysteresis loops, and therefore to reduce the impact of the diffraction contrast and reveal positions of the magnetic features more clearly, the aligned experimental images were enhanced using a high-pass filter and subsequent equalising the standard deviation across a series of images. The full processed data sets are shown in the Supplementary Material Figures S 2-4. Areas that have been strongly affected by diffraction contrast show reduced magnetic contrast, for example, in the right hand side of D1 from \(-69 \) mT to \(-199 \) mT. When the applied field direction is reversed in the hysteresis loop, the skyrmion contrast also reverses - i.e. skyrmion cores initially appear dark and change to appearing bright. The chirality of the skyrmions is preserved but their core magnetisation is reversed and therefore the contrast observed in the TEM is reversed. The transport of intensity equation (TIE) \[35\] was used to reconstruct the in-plane component of the magnetic flux density from the defocused images. For a one-sided TIE reconstruction, a single defocused image was used to reconstruct the flux density as described by Chess \[50\]. This technique is very sensitive to all changes in both magnetic and electrostatic potential and therefore significant edge effects are also observed at the sharp change in mean inner potential at the FeGe-Pt interfaces. For a more quantitative analysis of the phase variation
arising from skyrmions in these device shapes, off-axis electron holography is required where
a lower spatial resolution is obtained but any edge effects are not delocalised by the impact
of defocus.

The skyrmion-edge distance was measured by creating masks of the FeGe shapes, as for
the micromagnetic simulations (see Supplementary Material), and applying the masks to
each of the defocused images in each hysteresis loop. The masks were rescaled using the
calibration of the magnification change from in-focus to the defocus of the hysteresis loop.
An accurate measurement of skyrmion centre to edge distance was obtained from a normal
drawn between the defined device edge and the centre of the skyrmion.

II. DATA ACCESS STATEMENT

The micromagnetic simulation data that support the findings of this study are available
in Zenodo with the identifier 10.5281/zenodo.4270366. The experimental data supporting
the findings of this study are available within the paper [and its supplementary information
files].

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IV. AUTHOR CONTRIBUTIONS

A.C.T.-H. and H.F. conceived the idea for the study. J. Verezhak (University of Warwick,
U.K., now at PSI, Switzerland) and G.B. produced the FeGe crystal. A. Štefančič (University
of Warwick, U.K., now at PSI, Switzerland) selected the FeGe samples, A.C.T-H, J.C.L and
M.T.B produced FeGe lamellae with FIB and performed experimental measurements on
these. R.A.P and H.F performed the micromagnetic simulations. A.C.T.-H. and J.C.L
analysed the experimental images, and A.C.T.-H. and R.A.P compared the simulation data with the experimental data. All authors contributed to the interpretation of the results and the writing of the paper.

V. COMPETING INTERESTS

The authors declare no competing financial interests.

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FIG. 1. FeGe phase diagrams and electron micrographs of the dumbbell and block shapes (a) FeGe phase diagram (a) from AC susceptibility measurements showing regions of skyrmion lattice (SkL) for a bulk specimen and (b) from small angle x-ray scattering measurements for a comparably thin FeGe lamella. (c) Scanning electron micrograph after selective milling of the device shapes D1, D2, D3, B1 and B2 using the focused ion beam. The dashed white line indicates the position and extent of the final membrane. (d) Bright field TEM image of the thinned shapes. (e) TIE reconstruction of the magnetic induction of the helical phase in the shapes at 90 K. The colour wheel indicates the local direction of the in-plane magnetic flux density. (f) Colour map of the TIE reconstructed in-plane magnetic induction of the skyrmion phase from LTEM measurements at 262 K and an applied external magnetic field of 136 mT. The packing of the skyrmions is dependent on the geometry and ranges from square packing (as seen in D2) to pentagonal (D3) to the usual hexagonal (D2) coordination. Masks have been applied around each shape to show only the in plane magnetic induction in the FeGe shapes from the TIE reconstruction and therefore remove the strong intensity modulations arising from the sample edges.
FIG. 2. Variations in the helical phase within B1 and D3 from micromagnetic simulations and experimental data before and after an external magnetic field was applied. The magnetic structures formed in the block and dumbbell device shapes are compared using micromagnetic simulations and experimental data acquired at 90 K, 219 K and 245 K before and after an external magnetic field was applied. At 219 K and 245 K the helical phase fills the blocks and dumbbells with a single or slowly varying orientation of the wave vector, \( \mathbf{q} \), whereas at low temperatures the helical phase forms more complex, higher energy alignments of magnetisation after the application of an external magnetic field. A 3D visualisation of the simulated data is shown for dumbbell 3 which corresponds to the helical state before and after the external field was applied, viewed at 30° to the [\( \overline{2} \)11] axis.
FIG. 3. Behaviour of the devices under a varying applied external magnetic field at 90 K. Selected LTEM images acquired at 90 K. A direct correlation can be made between skyrmions present at high applied magnetic field (−313 mT, marked with coloured circles) and the helical rotations present at 0 mT (with corresponding coloured lines). Micromagnetic simulations showing the magnetisation of the device shapes reveal a close correlation to the experimental data.
FIG. 4. Selected images from the hysteresis loop series acquired at 245 K and 219 K
FIG. 5. Experimentally observed interaction of skyrmions with the device edges (a) Extracted images of device structure D2 at the lowest applied magnetic field (when increasing field from 0 mT) with skyrmions in the structure for 90 K (232 mT), 219 K (167 mT) and 245 K (134 mT) (b) Variation of measured skyrmion-edge distance ($d_{se}$) as a function of applied external magnetic field and temperature. Lines are plotted to reveal the trends of increasing skyrmion-edge distance with increasing temperature. Error bars represent the mean standard deviation for the skyrmion-edge distances measured at each temperature. (c) and (d) Sequential images from the hysteresis loop acquired of the FeGe device shapes at 245 K. With an increase in the (negative) applied external field between (c) −102 mT and (d) −134 mT the skyrmions in blue circles at the sharp internal corners of the dumbbell shapes disappear. The 70 nm red circles mark the position of skyrmions that remain in the shapes and move away from the edges as the applied field is increased. The right hand side of dumbbell D1 and block B1 have been significantly affected by strong diffraction contrast which reduces the observed magnetic contrast.
FIG. 6. **Plots of the total number of skyrmions in the device shapes**

Total number of skyrmions in all of the device shapes as a function of temperature, revealing a strong dependence on direction and magnitude of applied magnetic field (B). To allow a direct comparison between the device shapes, we divided the number of skyrmions by the measured surface area of each shape to calculate the skyrmion density. At 219 K we see the most hysteretic behaviour of the devices revealing that the energy barrier to form skyrmions from the cone phase is much larger than to form skyrmions from the helical phase. These plots reveal that skyrmion formation is enhanced in the dumbbell shapes where the number of skyrmions is higher at all fields and temperatures compared to the block shapes per unit area.