Fabrication and Characterization of Geometrically Confined Fe$_3$Sn$_2$

Skyrmion-based Devices

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ABSTRACT

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Skyrmion is a topologically protected nanometer-sized spin configuration, which makes it a promising candidate for future memory devices. All skyrmion applications are based on the formation and manipulation of spin textures in nanostructured elements. Therefore, fabrication of geometrically confined skyrmion-based nanodevices is an essential step in the investigation of skyrmion properties.

In this study, my research mainly focuses on the fabrication of high-quality Fe₃Sn₂ nanostripes with different geometric parameters for Lorentz transmission electron microscopy (LTEM) by a focused ion beam (FIB) system. The observation of the skyrmions using LTEM was mainly performed by Dr. Qiang Zhang, although I have deeply involved the discussion on new samples to be fabricated based on the results obtained from LTEM and also performed some LTEM experiments.

To investigate the formation process and thermal stability of skyrmions in a geometrically confined environment, I have fabricated more than fifty high-quality nanostripes with a width of 265-4,000 nm. Studying with LTEM, a distinct evolutionary path of stripe-skyrmion transformation is observed after gradually increasing the magnetic field (out-of-plane direction) and the critical magnetic field of skyrmion is found to decrease with an increasing strength of confinements. Moreover, a series of racetrack devices with controlled thicknesses (125–404 nm) is fabricated to study the effect of thickness in skyrmion formation.

Overall, in order to obtain less damaged, flat skyrmion-based devices by FIB system, experimental parameters are optimized and fabrication skills are improved. This method develops the possible application of centrosymmetric frustrated magnet Fe₃Sn₂ in skyrmion-based racetrack devices.

Keywords: Skyrmions, Focused ion beam system, Racetrack devices, Geometric confinement.
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Chapter 1 Introduction

Research background

Magnetic storage devices are the most efficient system to store large amounts of digital information and play a crucial role in modern life. Giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR) are representative technologies for these types of devices. The research groups of Albert Fert and Peter Grünberg independently discovered GMR in 1988 \cite{1} \cite{2} and were awarded the Nobel Prize in Physics in 2007 because of its numerous commercial applications and promising prospects. For instance, GMR can be applied in magnetic field sensors, which contain reading data in hard disk drives, microelectromechanical systems (MEMS), biosensors and other devices. However, due to their superparamagnetic limits, slow mechanical movement and high thermal fluctuation, traditional magnetic storage technology is limited.

In order to overcome the above problems, as well as to improve the “reading” and “writing” speed of magnetic storage devices, Stuart Parkin’s research group designed magnetic racetrack devices which use spin-polarized current pulses to successively create, move and detect domain walls \cite{3}. The magnetic racetrack device could be regarded as a type of non-volatile storage memory device which enables the domain walls to be written and shifted within tens of nanoseconds. Therefore, this group developed the idea of using the current to control domain walls, hence improving the speed of writing and reading.
Unfortunately, because of the general existence of impurities in magnetic materials, electrons scatter significantly during transmission. The heating problem becomes a major obstacle in the development of these devices and the current density usually reaches values as high as $10^{11}$ A/m$^2$. As a result, new materials with a higher storage density, better thermal stability and faster writing ability are required. In this respect, topologically protected materials stand out from competing materials.

### 1.1 Brief introduction to skyrmions

Skyrmion is a nanometer-sized topologically stable spin texture, and was first proposed by Tony Skyrme in the 1960s \[4\]. As shown in Figure 1.1, the spins inside a skyrmion rotate gradually from a downwards direction in the center to an upwards direction on the edge, under a settled chirality. Various situations are encountered in different magnetic skyrmions and these usually include two typical categories: Néel-type skyrmions (Figure 1.1b) and Bloch-type skyrmions (Figure 1.1c). In addition, skyrmions can be determined by the topological number $N$ (skyrmion number)\[5\]-\[6\], which is a measure of the winding of the normalized local magnetization, $n$. In a two-dimensional limit, the topological number can be calculated as follows:

$$N = \frac{1}{4\pi} \int \int d^2r n \star (\frac{\partial n}{\partial x} \times \frac{\partial n}{\partial y}) = \pm 1$$

There are numerous possible forms of skyrmion structures which correspond to different values of vorticity ($m$) and helicity ($\gamma$) \[7\], as shown in Figure 1.1d.
Figure 1.1 (a) Schematic of the spin-dependent skyrmion model. (b) Neel-type skyrmions \(^8\). (c) Bloch-type skyrmions \(^8\). (d) Various skyrmion structures with specific \(m\) and \(\gamma\) values. Arrows indicate the in-plane spin component direction and the brightness expresses the normal component of the plane, with white indicating the upwards direction and black indicating the downwards direction. \(m=1\) indicates clockwise in the \(x-y\) plane and \(m=-1\) indicates anti-clockwise in the \(x-y\) plane (anti-skyrmions) \(^9\).

1.1.1 Mechanisms that generate skyrmions

In magnetic systems, many energies such as exchange energy, anisotropy energy and magnetostatic energies compete with each other and contribute concurrently to generate skyrmions. A detailed introduction to these mechanisms now follows.

Dzyaloshinskii–Moriya interactions (DMIs) \(^{10,11}\) are named after Dzyaloshinskii and Moriya for their pioneering contribution of postulation. This antisymmetric exchange interaction is part of the total magnetic exchange interactions between the two
neighboring magnetic spins, $S_i$ and $S_j$, discovered by Igor Dzyaloshinskii and based on the Landau theory $^{[10]}$. Subsequently, Toru Moriya proved that spin-orbit coupling is the microscopic mechanism of DMI $^{[11]}$, which led to the definition of the DMI as:

$$H_{DM} \propto \int d\mathbf{r} \mathbf{M} \times (\nabla \times \mathbf{M})$$

The DMI favor chiral-lattice ferromagnets which have broken spatial inversion symmetry, such as B20 compounds ($\text{Fe}_{1-x}\text{Co}_x\text{Si}$, $\text{MnSi}$, $\text{FeGe}$,) and multi-layered thin films.

Ferromagnetic exchange interactions, which prefer a collinear ferromagnetic spin alignment $^{[4]}$, compete with DMI in a magnetic material, resulting in a helical spin order with a uniform turn angle in magnetic materials. In general, these two interactions can form skyrmions under a specific external magnetic field with a size of approximately 3–100 nm.

Meanwhile, long-ranged magnetic dipolar interactions are similar to ferromagnetic exchange interaction and favor in-plane magnetization.

Magnetic uniaxial anisotropy favors out-of-plane magnetization in some magnetic thin films or bulk materials. When competing with dipolar interactions, the materials first show the periodic stripe domain. The stripe state then turns into a periodic arrangement of magnetic bubbles or skyrmions after adding an external perpendicular magnetic field $^{[12-15]}$.

Further interactions such as frustrated exchange interactions $^{[16]}$ and four-spin exchange interactions $^{[17]}$ can also lead to atomic-sized skyrmion structures. In conclusion,
Skyrmions are the resulting spin textures of multiple mechanism competition.

1.1.2 Further applications and superiority

A skyrmion contains nano-sized structures, topologically protected properties and a number of other intriguing phenomena. As a result, it can behave as particles which have been moved, created (writing) and annihilated (deleting), which makes skyrmions suitable for spintronic applications particularly in memory devices and some logic technologies\textsuperscript{[16]}. The superiorities of a skyrmion are mainly focused on three aspects. First, a reduction in the storage disk size of approximately 20\%. Second, in comparison to current-driven domain walls, skyrmion-based logic devices can reduce the current density by five orders (and require approximately $10^6$ A/m\(^2\))\textsuperscript{[18]}. Third, the writing and deleting speed can be improved significantly in skyrmion-based racetrack devices because the current gains the ability to read data.

1.1.3 Three typical skyrmion material environments

Many skyrmion spin textures can be found in several magnetic material environments with noticeable features. Here we list three main magnetic systems\textsuperscript{[4]}. The first is non-centrosymmetric magnets, the second is centrosymmetric magnets with uniaxial anisotropy and the third is the surface/interface of thin film magnets. In non-centrosymmetric magnets and the surface/interface of magnets, the material systems break space-inversion symmetry, so the DMIs chiefly contribute to stabilizing the
skyrmions. In the case of centrosymmetric magnets, in comparison to the first and third types, the space-inversion symmetry is not broken, and the competition between magnetic anisotropies and dipole-dipole interaction is key in order to achieve magnetic skyrmions.

1.1.3.1 Skyrmions in non-centrosymmetric ferromagnets

These materials’ space-inversion symmetry is broken, and DMIs play the major role in stabilizing the modulated spin texture\(^{10}\)[11]. There are two main types of materials. One type of non-centrosymmetric magnet is B20 alloys, which include MnSi\(^{19}\)[20] and FeGe \(^{21}\). These usually exhibit a similar lattice structure to the MnSi structure shown in Figure 1.2a. The other typical example is the insulating material Cu\(_2\)OSeO\(_3\) \(^{22}\)[23], which contains two character-magnetic Cu\(^{2+}\) (S=1/2) sites with a local ferromagnetic spin arrangement between them (illustrated in Figure 1.2b).

These two material environments have the same chiral cubic space group P2\(_{1}\)3, and the ferromagnetic exchange interaction and DMIs are active \(^{24}\). In most cases, these materials can only form skyrmions in a low temperature, and the temperature range is very narrow (the Curie temperature is usually very low).

1.1.3.2 Skyrmions in centrosymmetric ferromagnets

In centrosymmetric magnetic materials, DMIs no longer exist. On the contrary, a combination of magnetic dipole-dipole interaction and uniaxial anisotropy results in the formation of a skyrmion spin texture. In traditional magnets, dipole-dipole interaction favors in-plane magnetization, which competes with magnetic anisotropy and leads to the
formation of several magnetic domain structures, such as BaFe$_{12-x}$Sc$_x$Mg$_{0.05}$O$_{19}$\textsuperscript{[25]}; this has no special chirality, so it can exhibit a rich abundance of spin textures.

![Figure 1.2](image1.png)

Figure 1.2 (a) MnSi crystalline structure\textsuperscript{[19]}, (b) Cu$_2$OSeO$_3$ crystalline structure\textsuperscript{[22]}.

![Figure 1.3](image2.png)

Figure 1.3 (a) Lorentz transmission electron microscope data during observation of BaFe$_{12-x}$Sc$_x$Mg$_{0.05}$O$_{19}$ materials. These images show the formation of skyrmion bubble formation with the increase of the magnetic field. Skyrmion and anti-skyrmion can be found distributed randomly throughout the material\textsuperscript{[25]}. (b) The transport-of-intensity simulation and mapping of the spins in skyrmions, with arrows indicating the spin direction\textsuperscript{[25]}.

1.1.3.3 Skyrmions at the interface

As discussed in section 1.1.3.1, DMIs usually occur in a material system with broken
spatial inversion symmetry, such as a non-centrosymmetric material system. DMIIs also occur in the interfaces or surfaces of ferromagnetism materials; for example, in the thin film materials illustrated in Figure 1.4 [26]. The PbFe layer only comprises one or two atomic units, and supplies magnetic moments with a ferromagnetic exchange interaction. The large atomic number of Ir provides a strong spin-orbit coupling and results in significant DMIIs. These skyrmions belong to the Neel type with sizes less than 10 nm, presenting the potential to act as information carriers for high-density storage and logic devices.

Figure 1.4 Forming skyrmions in thin film materials (PdFe bilayer on Ir (111) surface [26]). (a)–(c) Perspective sketches of magnetic phases. (d) Image under SP-STM with zero magnetic fields. (e)–(g) Formation process of skyrmions under an external magnetic field, showing changes from a mixture of spin-spiral and skyrmion phases to a skyrmion-only phase and finally to a ferromagnetic phase. (h)–(i) Use of the inducing current to manipulate skyrmions under 1.8 T at 4.2 K.

1.1.4 Brief summary of skyrmion material systems

As stated above, skyrmions in non-centrosymmetric magnets and thin film magnets are
mainly stabilized by DMIs. Large DMIs contribute to maintaining the stability of skyrmions, so these materials have great potential for design and use in possible spintronic devices. However, the Curie temperature of skyrmion materials tends to be very low (below room temperature) and the temperature range is extremely narrow, which limits their development in actual applications (as shown in Figure 1.5). Therefore, it is crucial to develop a magnetic material system that can form stable skyrmions above room temperature.

![Figure 1.5 Summary of the temperature range in DMI material system magnets under different external magnetic fields. Most form skyrmions below room temperature and have a narrow temperature range.](image)

No DMIs are found in centrosymmetric magnets, providing a rich abundance of skyrmions with different helicity and vorticity values. Studying the formation process in centrosymmetric magnets should help to fully understand skyrmion mechanisms.
1.2 Brief introduction to Fe$_3$Sn$_2$ magnetic materials

According to Pereiro et al.,\cite{27} Fe$_3$Sn$_2$ is a layered rhombohedral-structured material which has variable topological spin textures and good thermostability. As shown in Figure 1.6, Fe$_3$Sn$_2$ has an alternating structure along the c-axis which includes a pure Sn layer and Fe–Sn bilayers. The Fe atoms in bilayers form kagome networks, while Sn atoms are distributed within the kagome layers and between the kagome bilayers. The Fe$_3$Sn$_2$ material is a noncollinear frustrated ferromagnet with a 640 K Curie temperature and shows a spin reorientation whereby the Fe moments rotate step by step from the c-axis to the ab-plane with decreasing temperature\cite{28–31}. A large anomalous Hall effect was recently found in Fe$_3$Sn$_2$, which is closely correlated to the frustrated kagome Fe atom bilayer\cite{32}\cite{33}.

![Figure 1.6](image-url) (a) Fe$_3$Sn$_2$ crystal structure. The bottom left image shows Fe and Sn atoms as viewed from the top of the kagome layer, while the bottom right image indicates a possible spin (denoted by arrows) configuration of the Fe atoms. (b) The relationship between temperature and the anisotropy constant (Ku) in the temperature range 10–400 K. Insets (from right to left) schematically illustrate the angle between the magnetic easy axis and the c-axis at 300, 150 and 6 K, respectively.

In addition, as reported by Wenhong Wang\cite{34}, magnetic skyrmionic bubbles in Fe$_3$Sn$_2$
single crystals can remain stable at room temperature. This conclusion indicates that Fe$_3$Sn$_2$ materials could be a promising candidate for fabricating further skyrmion-based spintronic devices, due to their good thermostability.

In conclusion, the superiorities of investigating and developing Fe$_3$Sn$_2$ materials can be considered from three aspects.

First, Fe$_3$Sn$_2$ is a single-crystal material, so it is simple to fabricate into special structures along the unique axis. This is beneficial for the further design of skyrmion-based devices.

Second, Fe$_3$Sn$_2$ is a centrosymmetric magnet, so no DMIs control the formation of skyrmions. As a result, it is able to exhibit an abundance of skyrmions and magnetic spin structures, which helps to further understand skyrmion mechanisms.

Third, Fe$_3$Sn$_2$ has a high Curie temperature (640K) and very broad temperature zone and thus has the potential to stabilize skyrmions at a high temperature. This property should make it a promising material to produce skyrmion-based spintronic devices because ensuring electric-magnetic devices with good thermostability is necessary for applications.

1.3 Motivation to fabricate geometrically confined skyrmion-based devices

In order to translate the superiorities of skyrmions into applications, skyrmion-based devices must be designed as well as fabricated. Hence, controlling the formation and stability of individual skyrmions in these devices is a crucial step, so it is very important
to clearly understand the mechanisms taking place inside a highly geometrically confined environment.

Ever since Jonietz et al. \cite{35} performed an ultralow threshold current-driven motion ($\sim 10^5-10^6$ Am$^{-2}$) experiment in MnSi, topological skyrmions have been expected to be prospective information carriers for spintronic applications \cite{26} \cite{36-41}, particularly for racetrack memory devices \cite{37} \cite{42}. However, magnetic skyrmions usually demonstrate very low thermal stability and most are only stable below room temperature, which becomes a great problem and hinders their practical applications \cite{19} \cite{43-44}. Significantly, a geometrically confined FeGe nanostripe single skyrmion chain was fabricated by Du et al. \cite{45}, which improved the stable temperature range of skyrmions from 100 to 250 K. This experiment provided a new idea for the fabrication of skyrmion-based racetrack memory devices and provides some interesting results in a highly geometrically confined environment. Furthermore, in order to convert the single skyrmion chain into practical applications, a high thermal stability is also required. Furthermore, Zhipeng Hou et al. \cite{46} recently reported a frustrated Fe$_3$Sn$_2$ magnet, which shows that Fe$_3$Sn$_2$ can form skyrmionic bubbles at room temperature. However, the skyrmions still cannot achieve the thermal stability requirement of the practical electric devices. Therefore, further research into finding a high-temperature stability skyrmion system is urgently required. The fabrication of Fe$_3$Sn$_2$ magnet devices, which have a high geometric confinement, may be a good solution.

The most efficient way to fabricate geometric confinement devices for the Fe$_3$Sn$_2$
magnetic material is using a focused ion beam (FIB) system, which has the following advantages.

First, Lorentz transmission electron microscopy (LETM) is able to view magnetic skyrmions in real space and obtain visual spin structures. To date, it is the most important method used to characterize skyrmions. However, samples studied under LTEM are required to be very thin (usually about 100–300 nm) and uniform. Accordingly, the FIB system is the most effective way to fabricate samples for this purpose.

Second, Fe₃Sn₂ is a type of single-crystal material and the uniaxial anisotropy direction is along the c-axis. In order to obtain skyrmions clearly under LTEM, the anisotropy direction of the thin lamella should follow the normal (001) direction, which can be accurately controlled by the FIB system.

Third, the geometric confinement can be easily achieved by controlling the width and thickness of devices. The entire fabrication process can be tightly controlled.

1.4 Research contents

An abundance of topological skyrmions has been demonstrated in Fe₃Sn₂ materials, and these skyrmions have been shown to have excellent thermostability (even at room temperature). Many skyrmion materials, such as FeGe with geometric confinement, have been reported, but skyrmions in the frustrated single-crystal material have not been studied in a geometrically confined environment. Hence this project focuses on the fabrication of geometrically confined Fe₃Sn₂ skyrmion-based devices by FIB system and
further characterization by LTEM.

The details of this research are as follows:

1 Use of the FIB method to fabricate skyrmion-based nanostripe devices with single-crystal Fe₃Sn₂ material. These devices are deposited by electron-beam carbon, platinum and ion-beam platinum and then used to study the skyrmions’ thermal stability in highly geometrically confined materials.

2 Use of the FIB system to fabricate racetrack devices with different geometric confinements, controlling the widths and thicknesses, respectively. This is followed by observation of the skyrmion formation process in LTEM and examination of the phase change process in these devices.
Chapter 2 Experimental Apparatus

High-quality single-crystal Fe₃Sn₂ materials were synthesized by Dr. Zhipeng Hou⁴, using the Sn-flux method at the Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences. In this project, an in-depth and concrete study was then conducted on the fabrication and characterization of Fe₃Sn₂.

2.1 Focused ion beam system

The FIB facility is based on a scanning electron microscope (SEM) but with the electron beam replaced by an ion beam. In an SEM, the electron beams are focused on the sample surface and produce several signals by a scattering method, while a FIB system uses ions to interact with samples and subsequently form images. These ions are positively charged, large and slow moving. In comparison to general SEM, ion beams are more powerful and capable of removing sample atoms from the substrate.

Figure 2.1[47] Inner structures of SEM and FIB systems. Ions are used to replace electrons in FIB.
2.1.1 Principle of the FIB system

The FIB system operates using a similar mechanism to the SEM, except for the beam source. The ion beams should not only form images at low beam currents but also need to mill samples at high beam currents (usually gallium).

![Image of FIB system](image)

Figure 2.2[47] (a) Principle of the FIB system, which can perform the functions of milling (using Ga⁺) and deposition (carbon and platinum), making it an efficient micro-sized or nano-sized fabrication system[38]. (b) Image of the Helios Nanolab 400s FIB system.

As shown in Figure 2.2a, when the focused gallium (Ga⁺) ion beams reach the sample surface, some of the sample atoms are sputtered and the collision process generates secondary electrons (e⁻). The sputtered ions or secondary electrons are then collected to form the image. In a low-current mode, the FIB system can produce high-resolution images by using ion beams (the imaging resolution of Ga ions is about 5 nm[48]), while in a high-current mode the sample can be milled due to the high energy of the system. In this way, the special structure of the specimen and nano-sized TEM lamella can be fabricated.
2.1.2 The Helios Nanolab 400s FIB system

The FIB system used in this experiment is equipped with an SEM dual beam system (Helios Nanolab 400s). The FEI Helios NanoLab 400S FIB-SEM is one of the world’s most advanced dual beam FIB platforms and plays a vital role in the preparation of the high-resolution transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM) samples, SEM imaging, energy-dispersive X-ray analysis and nano-fabrication. It can also enable the deposition of carbon and platinum through the electron beam or the ion beam.\textsuperscript{[38]}

The Helios Nanolab 400s uses a liquid metal ion source (LMIS) and its energy can change from 1 to 30 KeV (kilo electron volts). Reasons for using gallium as the ion beam source are as follows:

- It is a liquid metal
- Room temperature operation is possible
- It has a long life (500–1,500 hours)
- It is high-vacuum compatible
- It has a large ion for sputtering and thus optimum momentum transfer capability
- It is a source of high brightness
- Low analytical interference (implantation) occurs and thus produces well-separated K-lines and exhibits limited overlap with other L-lines.

Primary components of the FIB system include an electron column, an ion column,
detectors, a gas injection system (GIS), an omniprobe and an energy-dispersive spectroscopy (EDS) system.

Furthermore, major capabilities of the FIB system are milling, deposition, micro- and nano-patterning, cross-section milling and imaging, and the creation of TEM lamella.

2.2 Transmission electron microscopy (TEM)

TEM is a microscopy technique whereby an electron beam is transmitted through a specimen to form an image. The specimen is usually ultrathin (less than 100 nm). Because the electron beam is transmitted through the specimen, the interaction between electrons and the sample causes the transmitted electrons to provide sufficient image-forming information. The image is then magnified and focused onto an imaging device, for instance, a fluorescent screen, a layer of photographic film or a sensor such as a charge-coupled device (CCD).

Because the wavelength of electrons is significantly shorter than the wavelength of light, TEM has a significantly higher resolution than light microscopes. Unlike light microscopes, TEM uses an electromagnetic lens instead of an optical lens and is thus capable of hitting the samples with higher energy (up to 300 kV).
2.2.1 The Titan G2 60-300 TEM

The Titan G2 60-300 S/TEM is equipped with a spherical aberration corrector to provide atomic-resolution imaging and spectroscopy, which brings the advantages of higher resolution, stability and flexibility. The flexible accelerated voltage ranges from 60 to 300 kV and can be used to characterize diverse materials. Furthermore, TEM utilizes several functions in order to provide detailed information about a material:

1. High-resolution TEM (HRTEM) is able to provide 70 pm of atomic-resolution imaging information.

2. In STEM, the electron beam is focused on a fine spot to scan the sample in a raster.

3. Energy-dispersive X-ray spectroscopy (EDX) is used for elemental analysis or the chemical characterization of a sample.
4. Electron energy loss spectroscopy (EELS) determines the type of atoms and the number of atoms of each type, especially for light elements.

5. In LTEM, the objective lens can provide a magnetic field and perform Lorentz mode imaging.

2.3 Lorentz transmission electron microscopy

In this study, LTEM is used as a mode of the Titan G2 60-300 TEM, where the objective lenses supply a magnetic field of up to 3,000 Oe in the perpendicular direction.

![Figure 2.4](image-url) (a) The Titan G2 60-300 TEM. (b) Fresnel-mode LTEM, collecting under-focus, in-focus and over-focus data to obtain magnetic information.

LTEM is employed for real-space observation of magnetic samples. When the incident electron beam transmits a magnetic sample, the electrons are influenced by the Lorentz force and exhibit divergence or aggregation. As a result, bright areas and dark areas are formed by the electron beams and show the contrast between over-focused and
under-focused images. Therefore, by collecting over-focused and under-focused images and processing them into a transport-of-intensity equation (TIE), the real-space distribution of in-plane components of local magnetizations can be obtained.
Chapter 3 Fabrication of Nanostripe Devices for Thermal Stability Investigation

As reported by Dr. Hou, the frustrated kagome Fe$_3$Sn$_2$ magnet has skyrmionic magnetic bubbles with variable topological spin textures at room temperature\cite{46}. During studying the skyrmion formation process in single-crystal Fe$_3$Sn$_2$, it was found that skyrmions usually occur along the boundary or at defects preceding to the central area (as shown in Figure 3.1). The phenomenon is called the “boundary effect” in this research. As a result, producing geometric confinement manually becomes desirable when studying skyrmion properties further.

3.1 Sample preparation

The high-quality Fe$_3$Sn$_2$ single crystal was provided by Dr. Hou and was synthesized using a Sn-flux method. X-ray diffraction and SEM were employed to characterize the typical single-crystal Fe$_3$Sn$_2$ (as shown in Figure 3.2a). The sample exhibited a hexagonal face normal to the [001] direction. After performing electron microscope scanning with energy-dispersive X-ray spectrometry (SEM-EDX) element mapping, the chemical composition ratio of Fe:Sn was found to be 60.85:39.15%, which is very close to the ideal ratio of 3:2. This measurement was performed on the polished hexagonal surface.
Figure 3.1 The skyrmion formation process in the thin-plate Fe₃Sn₂ material (thickness of about 250 nm) cut from the bulk single crystal. All patterns were imaged at the same position of the thin-plate Fe₃Sn₂ material and in under-focused LTEM mode at 300 K. The scale bar of all images is 500 nm. Some residual amorphous electron-beam carbon and platinum can be seen at the top boundary and some of the skyrmions occur first at the edge states.

Figure 3.2[46] (a) The X-ray diffraction pattern of a typical single crystal of Fe₃Sn₂. The inset shows an SEM image of a Fe₃Sn₂ single crystal produced by EDX element mapping.

3.2 Fabrication process of a nanostripe device

The experiment mainly used the FIB system to fabricate the Fe₃Sn₂ magnet, via the process shown in Figure 3.3a–f.[46]
Figure 3.3 Process diagram for preparing the geometrically confined LTEM sample. A (001) direction single crystal is produced using the FIB and scanning electron microscopy (FIB-SEM) dual beam system (Helios Nanolab. 600i, FEI) equipped with a GIS. (a) Using the gallium ion milling method to perform bulk milling, a thin lamella with a thickness of approximately 2,000 nm was revealed on the (001) surface of a Fe₃Sn₂ single crystal. (b) Deposition of electron-beam carbon, electron-beam platinum and ion-beam platinum on the surface of the Fe₃Sn₂ thin plate by using the GIS system to protect the edge of the nanostripes. (c) U-shaped cut made to cut the lamella almost free from the bulk. (d) Transfer of the lamella to a TEM Cu chip parallel to the horizontal plane. (e) Rotation of the TEM Cu chip by 90 degrees (the Cu chip is perpendicular to the horizontal plane) and thinning of the lamella along the horizontal plane. (f) SEM image of the nanostripe; this is the nano-racetrack device.

In order to obtain high-quality, less damaged and flat skyrmion-based devices, the experimental details are explored as follows:

(1) Employ a GIS to deposit ion-beam Pt (Figure 3.4), which is used for protecting the sample surface, with the experimental parameters shown in Table 3.1.
Figure 3.4 Deposition of the protective layer with ion-beam Pt.

Table 3.1 Experimental parameters for protective layer deposition.

<table>
<thead>
<tr>
<th>Stage tilt</th>
<th>52°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion beam voltage/current</td>
<td>30KV, 0.28nA</td>
</tr>
<tr>
<td>Pattern type</td>
<td>rectangle</td>
</tr>
<tr>
<td>Pattern area(X<em>Y</em>Z)</td>
<td>25um<em>3um</em>2um</td>
</tr>
</tbody>
</table>

(2) Use 30 kV gallium ions to perform bulk milling and intermediate milling (as shown in Figure 3.5) in order to lift out the lamella.

Figure 3.5 Milling samples with high-energy gallium ions
Table 3.2 Experimental parameters for milling

<table>
<thead>
<tr>
<th>Stage tilt</th>
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</thead>
<tbody>
<tr>
<td>Ion beam voltage/current</td>
<td>30kV, 93pA-21nA</td>
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<tr>
<td>Pattern type</td>
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<tr>
<td>Upper Pattern area (X<em>Y</em>Z)</td>
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</tr>
<tr>
<td>Lower Pattern area (X<em>Y</em>Z)</td>
<td>30um<em>10um</em>10um</td>
</tr>
<tr>
<td>Pattern application</td>
<td>Parallel</td>
</tr>
</tbody>
</table>

Figure 3.6 Producing geometric confinement. (a) Depositing electron-beam carbon and platinum. (b) Depositing ion-beam platinum.

(3) Thin the sample to the required thickness and deposit upon it electron-beam carbon, electron-beam platinum and ion-beam platinum, respectively. In order to produce the geometric confinement, the sample width is controlled and electron-beam carbon is first deposited on the surface of the material. Electron-beam carbon is light compared to platinum, so its damage to the material surface is low and it can further protect the material. Electron-beam platinum and ion-beam platinum are deposited later. All of these deposits not only play a vital role in protecting the sample during thinning process but
also reduce the effect of Fresnel fringes on the edge of the device and enable us to get clear images of the nano-sized magnetic structure under LTEM. Detailed information is shown in Figure. 3.6. The deposition parameters are shown in Table 3.3, 3.4 and 3.5.

Table 3.3 Experimental parameters for depositing electron-beam carbon

<table>
<thead>
<tr>
<th>Stage tilt</th>
<th>52°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam voltage/current</td>
<td>5KV, 1.4nA/2.7nA</td>
</tr>
<tr>
<td>Deposition source</td>
<td>Electron beam carbon</td>
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<tr>
<td>Pattern area(X<em>Y</em>Z)</td>
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</tr>
</tbody>
</table>

Table 3.4 Experimental parameters for depositing electron-beam platinum

<table>
<thead>
<tr>
<th>Stage tilt</th>
<th>52°</th>
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</thead>
<tbody>
<tr>
<td>Electron beam voltage/current</td>
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</tr>
<tr>
<td>Deposition source</td>
<td>Electron beam platinum</td>
</tr>
<tr>
<td>Pattern area(X<em>Y</em>Z)</td>
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</tr>
</tbody>
</table>

Table 3.5 Experimental parameters for depositing ion-beam platinum

<table>
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<tr>
<th>Stage tilt</th>
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<tbody>
<tr>
<td>Ion beam voltage/current</td>
<td>30KV, 0.28nA</td>
</tr>
<tr>
<td>Deposition source</td>
<td>Ion beam platinum</td>
</tr>
<tr>
<td>Pattern area(X<em>Y</em>Z)</td>
<td>25um<em>3um</em>2um</td>
</tr>
</tbody>
</table>

(4) Use the gallium ion beam to make a U-shaped cut under stage 0° tilting. Ensure that the Lamella is completely cut free at the left side (where the omniprobe enters) and the bottom side. Then carefully insert the omniprobe and lift out the cuboid to attach it to
the TEM Cu chip, which is parallel to the horizontal plane. Finally, the TEM Cu chip is rotated by 90° (the Cu chip is perpendicular to the horizontal plane) and the cuboid is thinned along the horizontal plane by Ga ion beams. In order to find the effective way to perform the thinning work, the thinning parameters are explored as follows. It includes three steps, which are shown in Table 3.6, 3.7 and 3.8, respectively.

Table 3.6 Experimental parameters for thinning lamella to 1,000 nm

<table>
<thead>
<tr>
<th>Ion beam voltage/current</th>
<th>30KV/2.8nA</th>
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</thead>
<tbody>
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<td>Pattern type</td>
<td>Rectangle</td>
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<tr>
<td>X<em>Y</em>Z(um) Stage tilt</td>
<td>Direction</td>
</tr>
<tr>
<td>Upper pattern</td>
<td>25<em>1</em>6</td>
</tr>
<tr>
<td>Lower pattern</td>
<td>25<em>1</em>6</td>
</tr>
</tbody>
</table>

Table 3.7 Experimental parameters for thinning lamella to 400 nm

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<th>Ion beam voltage/current</th>
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</thead>
<tbody>
<tr>
<td>Pattern type</td>
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<tr>
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<td>Direction</td>
</tr>
<tr>
<td>Upper pattern</td>
<td>25<em>1</em>6</td>
</tr>
<tr>
<td>Lower pattern</td>
<td>25<em>1</em>6</td>
</tr>
</tbody>
</table>
Table 3.8 Experimental parameters for thinning lamella to 250 nm

<table>
<thead>
<tr>
<th>Ion beam voltage/current</th>
<th>30KV/93pA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern type</td>
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<tr>
<td>X<em>Y</em>Z(um)</td>
<td>Stage tilt</td>
</tr>
<tr>
<td>Upper pattern</td>
<td>25<em>0.5</em>5</td>
</tr>
<tr>
<td>Lower pattern</td>
<td>25<em>0.5</em>5</td>
</tr>
</tbody>
</table>

(5) Finally, the lamella is cleaned by a low-energy ion beam, and the racetrack device with a normal direction easy-anisotropy direction is fabricated.

Table 3.9 Experimental parameters for cleaning lamella

<table>
<thead>
<tr>
<th>Ion beam voltage/current</th>
<th>5KV/28pA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern type</td>
<td>Rectangle</td>
</tr>
<tr>
<td>X<em>Y</em>Z(um)</td>
<td>Stage tilt</td>
</tr>
<tr>
<td>Upper pattern</td>
<td>25<em>2</em>0.5</td>
</tr>
<tr>
<td>Lower pattern</td>
<td>25<em>2</em>0.5</td>
</tr>
</tbody>
</table>

3.3 Fabrication and characterization of nanostripe devices

Practical electric-magnetic devices require high thermal stability of the digital carriers (usually higher than room temperature). The Fe₃Sn₂ single crystal is a kind of frustrated ferromagnetic material with a very high Curie temperature Tc (up to 640 K). As a result, it is a good candidate to further study temperature stability and is expected to demonstrate
superior high-temperature stability in spintronic devices.

In this experiment, nanostripe devices with two different widths (600 nm and 4,000 nm) were fabricated to perform the control test.

### 3.3.1 Nanostripe devices with widths of 600 nm and 4,000 nm

As shown in Figure 3.7a–b, two nanostripe devices with different widths were prepared by a FIB system, both with nanostripe thicknesses of approximately 200 nm as shown in Figure 3.7c (200±20 nm). The devices both possessed a flat and uniform thickness, which indicates high quality. The 4,000 nm-wide nanostripe device has a weak geometric confinement effect while the 600 nm-wide nanostripe device has an obvious geometric confinement effect. Therefore, by comparing the two experiments, the influence on geometric confinement is understood.

Figure 3.7[46] The two nanostripe devices, both pictures taken by SEM with the Helios Nanolab 400s FIB system. (a) The 4,000 nm nanostripe device fabricated by the FIB, with a thickness of about 200 nm and length of about 25,000 nm. (b) The 600 nm nanostripe device fabricated by the FIB, with a thickness of about 200 nm and length of about 25,000 nm. (c) Analysis of sample thickness at the eight different sample positions. The pattern indicates that the nanostripe thickness is about 200±20 nm, and looks very uniform.
3.3.2 Characterization by high-resolution TEM

In order to further investigate the crystal structure of the nanostripe device sample, high-resolution transmission electron microscopy (HRTEM) was employed to produce the results shown in Figure 3.8a–e. These TEM images were obtained along the (001) direction of the Fe₃Sn₂ single crystal after fabrication of nanostripe devices. Figures (a) and (b) show the diffraction pattern of the material, with angles $\angle AOB=58.68^\circ$, $\angle BOD=61.72^\circ$ and $\angle DOE=59.68^\circ$. All of these values are close to the calculated values of 60°. The aberration-corrected STEM experiment was then operated to examine the atom-level information shown in Figures (c) and (d), from which it was found that the material shows an obvious hexagonal lattice structure. Finally, the corresponding Fourier transform pattern is shown in Figure (e). The angles $\angle AOB=58.95^\circ$, $\angle BOD=61.40^\circ$ and $\angle DOE=59.84^\circ$ are all close to the calculated values of 60°. As a result, the nanostripe Fe₃Sn₂ single-crystal material shows a perfect six-fold symmetric structure and retains good quality after fabrication. Furthermore, some minor strain is found in the material which may be possibly caused by FIB (Ga⁺ injecting).
3.4 Thermal stability study

Using the two high-quality nanostripe devices, Zhipeng Hou and Qiang Zhang further found that the geometric confinement effect significantly increased the thermal stability of skyrmions in the nanostripe device \cite{46}. The skyrmions can be kept stable from room
temperature to 630 K in the 600 nm nanostripe device, which is a record high-temperature stability for skyrmion host materials or devices.
Chapter 4 Fabrication of Racetrack Devices with Different Geometric Confinements

In this chapter, experiments are divided into two parts according to the controlled variables, which include width-controlled and thickness-controlled.

4.1 Width-controlled racetrack devices

4.1.1 Fabrication of racetrack devices with different widths

In racetrack devices the Fe$_3$Sn$_2$ single crystal is located in the middle (Figure 4.1), and the formed skyrmion size is approximately 280nm. Therefore, it is predicted that the boundary effect plays a more and more important role in skyrmion formation process in some highly geometric confinement environment. The width of a Fe$_3$Sn$_2$ material is a major geometric confinement factor that influences the formation of skyrmions. In this work, a series of racetrack devices with different widths is fabricated with almost the same thickness as shown in Figure 4.1. The width varies from 265 nm to 4,000 nm because we find that there is almost no geometric confinement influence exists in 4,000 nm device $^{[34]}$. The protected layers are always the same because the deposits are also amorphous electron-beam carbon, electron-beam platinum and ion-beam platinum, and all the devices have a length of about 25,000 nm and a thickness of about 200 nm. Hence, these are a series of controlled experiments.
Figure 4.1 (a)–(l) Racetrack devices with different widths, with the Fe₃Sn₂ single crystal width shown in the pattern below Wy and ranging from about 265 to 4,000 nm.

In this part, the racetrack device width should be controlled during the intermediate milling process, where the challenge is how to precisely control it. Because the gallium ion beam experiences an energy decrement after hitting the sample, uniform thinning cannot be maintained along the different sample depths. In order to obtain the horizontal thickness of the lamella in this process, tilting the stage to 53° was found to be a suitable solution when milling the lower pattern (both sides can be milled by a lower pattern with rotating stage). In case the lamella becomes curved during later deposition, one side should be deposited first before starting to mill the lamella to the ideal thickness. Because the target lamella is still attached to the bulk sample, nanometer-sized measurement is very difficult after deposition on one side. The effective solution is to expand the milling length and perform the same thinning work on the edge parts (no deposition), then the
measurement data for the edge part can be accepted.

4.1.2 Skyrmion formation process in racetrack devices

To further study the influence of width geometric confinement on skyrmion formation, a series of skyrmion formation processes were researched using LTEM. This makes it possible to obtain a clear image of the detailed transition process and a detailed critical magnetic field when skyrmions form. The observation of the skyrmions using LTEM was mainly performed by Dr. Qiang Zhang, although I also performed some.

![Figure 4.2 The magnetic spin texture formation process for a racetrack device with 4,000 nm width. All patterns were taken at the same position of the racetrack device and in under-focused LTEM mode at 300 K. The scale bar of all images is 500 nm and the sample thickness is about 200 nm.](image)

As shown in Figure 4.2, the racetrack device with a width of 4,000 nm is 14 times wider than in previous research carried out by Hou [46] (the diameters of skyrmions in the Fe₃Sn₂ material is about 280 nm), and thus is almost without geometric confinement. The
entire experiment was performed at about 300 K.

Initially, stripe domains occur in zero magnetic fields. With the increase of the magnetic field in the (001) direction (from 0 to 230 mT), the stripe domains shrink and the number decreases. Bubbles occur when the magnetic field reaches 300 mT, so that 300 mT is the critical magnetic field of 4,000 nm racetrack devices.

Figure 4.3 shows the process of skyrmion formation within a 2,500 nm-wide racetrack device. The skyrmions occur first at 220 mT. At 260 mT, all of the stripe domains disappear and change to skyrmions. This demonstrates that the geometric confinement factor had some obvious influence on skyrmions because the critical magnetic field decreased from 300 to 260 mT.

![Figure 4.3](image)

Figure 4.3 The skyrmion formation process for a racetrack device with 2,500 nm width. All patterns were taken at the same position of the racetrack device and in under-focused LTEM mode at 300 K. The scale bar of all images is 500 nm and the sample thickness is about 200 nm.

Figure 4.4 shows the process of skyrmion formation within a 1,600 nm-wide racetrack device. The skyrmions first occur at 140 mT and all of the stripe domain disappears and
changes to skyrmions at 220 mT. The critical magnetic field decreased to 220 mT.

Figure 4.4 The skyrmion formation process for a racetrack device of 1,600 nm width. All patterns were taken at the same position of the racetrack device and in under-focused LTEM mode at 300 K. The scale bar of all images is 500 nm and the sample thickness is about 200 nm.

Figure 4.5 The transformation process of skyrmions for 600 nm-width racetrack devices (having the same width). All patterns were taken at the same position of the racetrack device and in under-focused LTEM mode at 300 K. The scale bar of all images is 500 nm and the sample thickness is about 200 nm. (a) The first five pictures show the formation process for a sample of 200 nm thickness. When a
magnetic field is not present it shows the stripe domain, while the stripe domain shrank with an increasing magnetic field. Skyrmions first occur under 80 mT. (b) Magnetic TIE analysis illustrates the altered processing of magnetic moments by adding a magnetic field.

Figure 4.5 shows the process of skyrmion formation within a 600 nm-wide racetrack device. It shows a stripe domain below 60 mT, while skyrmions occur at about 80 mT. When the magnetic field is above 120 mT some of the skyrmions disappear gradually.

Figure 4.5 shows analysis by magnetic TIE, which illustrates the direction of magnetic moment on the racetrack devices.

Figure 4.6 shows the process of skyrmion formation within a 250 nm-wide racetrack device. No skyrmions appear.

Figure 4.6 shows the process of skyrmion formation within a 250 nm-wide racetrack device. Skyrmions can no longer be formed in this nanostripe.

4.1.3 **Summary and discussion of skyrmion topology transition**

The investigation into the skyrmion formation process in racetrack devices reveals an obvious skyrmion topology transition process during an increase in the magnetic field (out-of-plane direction). Furthermore, the width has an influence on the transformation. A
A summary of the topology transition process in racetrack devices of differing width is shown in Figure 4.7.

![Figure 4.7 Magnetic spin texture topology transition diagram, with width under magnetic field along the (001) direction as the independent variable.](image)

As seen in Figure 4.7, the magnetic critical field that forms skyrmions clearly declines with decreasing width (from 280 mT at 4,200 nm, 240 mT at 3,200 nm, 200 mT at 2,500 nm, 170 mT at 1,800 nm and 110 mT at 500 nm to 80 mT at 200 nm). Moreover, it is evident that once the racetrack reaches a specific width (approximately 3,000 nm) it does not form skyrmions, but only bubbles. When the racetrack width is between 1,800 nm and 2,500 nm, bubbles and skyrmions are in the mixed state. At a width of between 200 nm and 1,800 nm, skyrmion spin textures are formed when the critical field is met. When the width is below 200 nm, vortices (half skyrmions) are formed instead of skyrmions.
To illustrate the physical origin of the width confined effect, we extracted the in-plane spin distributions of the magnetic domains in the evolution process by using the TIE to analyze the over- and under-focused LTEM images. Figure 4.8g-i shows the spin textures of magnetic domains enclosed by white boxes in Figure 4.8c, e, and f, respectively. In a zero magnetic field, the spin helix shows perpendicular stripe domain and terminates at the upper and lower edges (see Figure 4.8g). With the increase of magnetic field, the in-plane component of the spin helix at the edges gradually increases and encloses two neighboring helixes into a whirly configuration. By increasing the magnetic field up to 80 mT, the spins at lower edges rotate first, which lead to the shrinkage of the domain and their separation from the lower boundary forming a skyrmion-like state (see Figure 4.8h). We propose the dipole-dipole interaction (DDI) at the edges act as an unbalanced torque on the edge spins which induces them gradually to lay down on the in-plane direction to form a closed loop by connecting with neighboring two helixes and further form the skyrmion-like state with the increase of magnetic field. This phenomenon is resulted by boundary effect. When the magnetic field increases up to 130mT, the spins are lifted away from the upper edge and finally evolve into the skyrmions.

However, for the sample without width confinement, the stripe domain is very long and it needs to break into many bubbles at first [34]. Then the bubbles can form skyrmions with increasing magnetic field, so the sample needs much more energy to form skyrmions. As sample width narrows down, the boundary effect plays a more and more important role in the skyrmion formation process, hence, the critical magnetic field of skyrmion is
found to decrease with an increasing strength of confinements.

![Figure 4.8](image)

**Figure 4.8** Evolution process of magnetic domains induced by external magnetic field for Fe₃Sn₂ nanostripe with a length 20μm, width 600nm, and thickness 250nm. (a) Schematic view of the Fe₃Sn₂ nanostripe (b) A typical STEM image of the 600nm wide nanostripe (left panel) and its corresponding SAED. The six-fold symmetry suggests the beam is along the [001] axis. (c-f) The under-focused LTEM images under different out-of-plane magnetic fields at 300K. The domain enclosed by white boxes present a one-to-one correspondence in the stripe-bubble transformation. The scale bar is 500nm. (g-i) Magnetization textures obtained from the TIE analysis for the domains enclosed by white boxes in c, e, and f. (j-m) The variation of skyrmion morphology as the decrease of magnetic field. The scale bar is 500nm.

### 4.2 Thickness-controlled racetrack devices

In most cases, the lamella thickness for the TEM is less than 100 nm and the lamella are used for taking high-resolution images. Using LTEM to view skyrmions in samples is
different to using TEM, so the influence of thickness should be explored for the formation of skyrmions in the Fe$_3$Sn$_2$ material.

![Image](image.png)

Figure 4.9(a)–(b) The five studied racetrack devices, with thicknesses ranging from 168 to 404 nm.

As shown in Figures 4.9a–b, segments with different thicknesses ranging from 168 to 404 nm are produced in the nano-racetrack devices during fabrication. These segments are produced following exactly the same processes, including deposition, milling and thinning, so that controlled characterization can be achieved. However, the nano-racetrack device is very easy to bend after hitting by electron beams under LTEM, and many stresses are produced.

Some modifications were then performed to fabricate the racetrack devices between two copper chips (as shown in Figure 4.10). This modification method uses two sides of copper chips to maintain the stability of the sample. This operation can effectively reduce the material bending problem during experiments. Following modification, the sample has fewer strains, and many clear skyrmions can be seen even under longer periods of time in a magnetic field.
Figure 4.10(a)–(g) Schematic image of the modification process and two completed samples. (a) A rectangular hole is cut on the Cu grid. (b) The deposited lamella are placed into the rectangular hole of the Cu grid. (c) The two sides of lamella are stuck with the Cu grid. (c)–(e) Two samples with different segment thicknesses of 134 nm and 296 nm, respectively. (f)–(g) Four samples with different segment thicknesses of 125.9 nm, 215.8 nm, 251.8 nm and 305.8 nm.

Using these racetrack devices, Zhipeng Hou and Qiang Zhang further found that the thickness of racetrack devices has a significant influence on the diameter of skyrmions but almost no influence on the skyrmions formation process under magnetic fields. With decreasing thickness, the diameter of skyrmions is reduced.
Chapter 5 Conclusions

This research first fabricated single-crystal Fe$_3$Sn$_2$ (exhibiting a high Curie temperature $T_c$ of up to 640 K) into a series of racetrack devices using the FIB system and these devices were deposited by electron-beam carbon, electron-beam platinum and ion-beam platinum. The devices’ confinement factors of widths and thicknesses were controlled accurately, and the optimized experimental parameters and fabrication skills were explored. A skyrmion topology transition process was evident during the increase in the magnetic field (out-of-plane direction) under LTEM. Using geometric confinement of the width, the evolutionary path of stripe-skyrmion transformation was altered and the skyrmions’ critical magnetic field was decreased. In order to develop a deep understanding of skyrmion formation mechanisms in racetrack devices, a topological transition phase diagram of skyrmions was then constructed.

Furthermore, two high-quality nanostripes (4,000 nm and 600 nm) were fabricated by adding geometric confinement to two sides of the materials. Subsequently, project collaborators obtained skyrmions with extremely high thermal stability in a 600 nm nanostripe device. These skyrmions remain stable when the temperature rises from room temperature to 630 K, which is a record high-temperature stability for skyrmion host materials or devices (as shown in Figure 5.1). This significantly wide thermal stability range (room temperature to 630 K) builds a solid foundation for further practical skyrmion-based applications.
Figure 5.1\textsuperscript{[46]} (a) Results of skyrmions’ highest stable temperature in non-centrosymmetric and centrosymmetric materials. The data is taken from references [21], [22], [45] and [50-54]. (b) Schematic diagram of the 600 nm nanostripe Fe$_3$Sn$_2$ geometric confinement device.
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1979.


