

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

NUCLEATION OF SKYRMIONIUMS AND THEIR DYNAMICS
IN THE PRESENCE OF DEFECTS

AYKUT CAN ÖNEL
A THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
DEPARTMENT OF PHYSICS

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SUPERVISOR
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GEBZE TEKNİK ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

SKYRMIONUMLARIN OLUŞTURULMASI
VE KUSURLAR İLE ETKİLEŞİMLERİNİN
İNCELENMESİ

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GEBZE
2023

GTÜ Fen Bilimleri Enstitüsü Yönetim Kurulu'nun 13/07/2023 tarih ve 2023 /39 sayılı kararıyla oluşturulan jüri tarafından 20/07/2023 tarihinde tez savunma sınavı yapılan Aykut Can Önel'in tez çalışması Fizik Anabilim Dalında DOKTORA tezi olarak kabul edilmiştir.

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...../...../..... tarih ve/..... sayılı kararı.

SUMMARY

This thesis presents a comprehensive study on the dynamics of skyrmionium in magnetic multilayers. The research is primarily focused on understanding the effects of interface roughness and engineered defects on the motion of skyrmionium.

The experimental part of the research involves the use of X-ray Reflectivity (XRR) to analyse the interface roughness of a multilayered sample. Roughness height measured from the XRR results were used in the simulations to investigate the interactions between random roughness and skyrmioniums.

The numerical simulations are conducted to study the motion of skyrmionium over a surface characterized by random roughness. The simulations are performed for varying average peak heights while keeping the size and distribution of the grains constant. The results show that as the grain height increases, the skyrmionium starts to "creep" from one grain to another, moving from one potential well to another.

The study then shifts its focus to investigate the effect of engineered defects on the skyrmionium. The results show that even a minor disturbance of 0.1 nm in the z-axis can hinder the skyrmionium's motion at low current densities. As the defect depth increases, the critical current density required for motion also rises, but no transformation occurs until a depth of 0.3 nm is reached. At this depth, a transformation to a skyrmion is observed within a certain range of current densities. However, as the defect depth increases to 0.4 nm, the skyrmionium can no longer pass through the defect as itself due to the amplified change in the effective field within the defect and the increased repulsive forces exerted by its walls. Consequently, a higher current density is needed for a skyrmionium to traverse this defect without transforming. However, at greater depths, increasing the current density will only lead to deformation of the skyrmionium. Therefore, in this model, the upper limit for the transition process is a defect depth of 0.4 nm. The findings from this research could have significant implications for the design and development of future magnetic storage devices.

Key Words: skyrmionium, defect, thickness modulation, micromagnetics

ÖZET

Bu tez, skyrmionium'un manyetik çoklu katmanlardaki dinamikleri üzerine kapsamlı bir çalışma sunmaktadır. Araştırma, öncelikle arayüz pürüzlülüğünün ve suni kusurlarının skyrmionium'un hareketi üzerindeki etkilerini anlamaya odaklanmıştır.

Araştırmanın deneysel kısmı, çok katmanlı bir numunenin arayüz pürüzlülüğünü analiz etmek için X-ışını Yansıtma (XRR) tekniği kullanılmıştır. XRR sonuçlarından ölçülen pürüzlülük değerinin simülasyonlarda pürüzlülük ve skyrmioniumlar arasındaki etkileşimleri araştırmak için kullanılmıştır.

Simülasyonlar, skyrmionium'un pürüzlülük ile karakterize edilen bir yüzey üzerindeki hareketini incelemek için yürütülmüştür. Simülasyonlar, tanelerin boyutunu ve dağılımını sabit tutarken ortalama tepe yükseklikleri için her simülasyonda değiştirilmiştir. Sonuçlar, tepe yüksekliği arttıkça skyrmionium'un bir taneden diğerine "sürünmeye" başladığını göstermiştir.

Çalışma daha sonra odağını, tasarlanmış kusurların skyrmionium üzerindeki etkisini araştırmaya kaydırmıştır. Sonuçlar, z eksenindeki 0,1 nm derinliğe sahip bir kusurun bile düşük akım yoğunluklarında skyrmionium'un hareketini engelleyebileceğini göstermiştir. Kusur derinliği arttıkça, hareket için gerekli olan kritik akım yoğunluğu da artmış ve 0.3 nm kusur derinliğinde belli bir kritik akım değerine kadar skyrmionium kusur içinden geçerken skyrmion'a dönüştüğü görülmüştür. Bununla birlikte, kusur derinliği 0,4 nm'ye çıkarıldığında, kusur içindeki efektif alandaki artış ve nedeniyle skyrmionium'un kusur içinden her geçişinde skyrmiona dönüştüğü gözlemlenmiştir. Sonuç olarak, bir skyrmionium'un bu kusuru dönüşmeden geçmesi için daha yüksek bir akım yoğunluğuna ihtiyaç vardır. Bununla birlikte, daha büyük derinliklerde, akım yoğunluğunun artırılması yalnızca skyrmionium'un deformasyonuna yol açacaktır. Bu nedenle, bu modelde geçiş süreci için üst sınır, 0,4 nm'lik bir kusur derinliğidir.

Anahtar Kelimeler: skyrmionium, kusur, kalınlık modülasyonu, micromanyetik

ACKNOWLEDGEMENTS

Firstly, I would like to express my deepest gratitude to my supervisor Prof. Dr. Bulat Rameev, whose expertise, understanding, and patience added considerably to my graduate experience. I would also like to express my gratitude to Dr. Mustafa Arıkan without whom I wouldn't be able to finish my PhD.

I am thankful to Dr. Arif Emre Yarımbyık, Serkan Sırt, Emrah Anigi, Dr. İlknur Gündüz Aykaç, Dr. Okan Özdemir and İbrahim Saim Ünver, for their understanding and support. I would like to express my gratitude to my colleagues and the staff at Gebze Technical University and Tübitak National Metrology Institute, for fostering an environment of intellectual curiosity and continuous learning. I would also like to extend my gratitude to Deniz Özbek Koçak and Can Koçak. Their camaraderie and support were invaluable throughout this journey.

To my family and my late father, thank you for your unwavering belief in my capabilities and for your constant support and encouragement. This achievement would not have been possible without your love and strength.

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LIST OF ABBREVIATIONS AND ACRONYMS

<u>Abbreviations</u> <u>and Acronyms</u>	<u>Explanations</u>
α	: Damping Factor
A_{ex}	: Exchange Stiffness
AFM	: Anti-Ferromagnetic
D_{ind}	: Interfacial Dzyaloshinskii-Moriya Constant
D	: Dissipative Tensor
DMI	: Dzyaloshinskii-Moriya Interaction
FM	: Ferromagnetic
HM	: Heavy Metal
J	: Exchange Integral
K_1	: 1 st Order Anisotropy Constant
M_s	: Saturation Magnetization
N_{sk}	: Skyrmion Number
θ_{sh}	: Spin-Hall Angle
SkHE	: Skyrmion Hall Effect
SHE	: Spin Hall Effect
STT	: Spin Transfer Torque
SOT	: Spin Orbit Torque
XRD	: X-Ray Diffraction
XRR	: X-Ray Reflectivity

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1. INTRODUCTION

Skyrmions, first introduced by T. Skyrme [1], are topological solitons that have found applications in the field of condensed matter physics. In magnetism, skyrmions are represented as the vortex like arrangements of the magnetic moments [2]. Due to their topologically non-trivial spin textures, skyrmions exhibit exceptional stability and resilience. They can maintain their structural integrity and energy levels with high efficiency, even when subjected to motion or external disturbances. These properties of skyrmions have generated significant attention regarding their practical implementations. Magnetic Skyrmions were first observed experimentally in bulk materials with chiral crystal structures, such as MnSi [3]. Materials that exhibit chirality are characterised by the lack of inversion symmetry, which allows for the emergence of the Dzyaloshinskii-Moriya Interaction (DMI) [4,5], a crucial factor in the formation of skyrmions. This interaction favours non-collinear alignment of spins, providing the necessary environment for skyrmion formation. However, skyrmion formation in MnSi requires low temperatures and external magnetic fields. This incited researchers to explore alternative platforms that could support the existence of skyrmions in ambient conditions. DMI can emerge at the interface between distinct layers in bilayer or multilayer structures [6]. The breaking of inversion symmetry at the interface, combined with strong spin-orbit coupling in some materials, leads to DMI. An example of a multilayer stack involves the presence of a ferromagnetic layer, such as Co or Fe, in conjunction with a heavy metal layer possessing strong spin-orbit coupling, such as Pt or Ta. In such a scenario, a notable interfacial DMI may arise. The interfacial DMI plays a crucial role in the formation and stabilization of skyrmions at room temperature in thin film structures [2]. Room-temperature skyrmions have been observed in multilayer structures composed of heavy metal and ferromagnetic layers, such as Pt/Co [7]. Sampaio et al. demonstrated that a single skyrmion can exist at stable conditions in Pt/Co bilayer structures. They also showed that spin-polarized current can be used to create skyrmions at local points. Furthermore, they found that these skyrmions can be manipulated and moved by using spin-polarized currents. In addition to studying the stability and nucleation of skyrmions, Sampaio et al. also investigated the current-induced motion of these structures. They found that spin transfer torques can be used to move individual skyrmions or chains of skyrmions in racetracks [7].

However, despite these advantages, the motion of a skyrmion is impeded from following a linear path along the direction of the driving current due to the Magnus Force which causes a deviation on skyrmion trajectory [8]. This phenomenon is called Skyrmion Hall Effect (SkHE) and it is one of the major obstacles in skyrmionics, because it introduces complexities in the precise manipulation of skyrmion movement. The SkHE is largely caused by the topological charge of the skyrmion. The topological charge, also known as the winding number, quantifies the number of times that the spins wrap around a unit sphere in spin space. A single skyrmion is characterized by a topological charge of +1 or -1, depending on the direction of the spin spiral, clockwise or counterclockwise [2]. This intrinsic property of the skyrmion is what makes it stable against minor perturbations and offers its unique stability, but it also results in the SkHE. Various solutions have been proposed by researchers to alleviate or eradicate the SkHE. One of the solutions proposed is using of antiferromagnetically coupled skyrmions [9,10]. This is achieved by coupling two ferromagnetic (FM) sublayers that are perpendicularly magnetised and strongly coupled through the antiferromagnetic (AFM) exchange interaction. When a skyrmion is nucleated/created at one of the layers results with the creation of an another skyrmion in the other FM layer, provided that the interlayer antiferromagnetic exchange coupling exhibits sufficient strength [9]. Another solution to SkHE is using skyrmioniums [11–14] instead of skyrmions. A Skyrmionium is comprised of two concentric skyrmions with opposite topological charges, resulting in a net zero topological charge. This configuration allows them to move directly along the current with no or minimal transverse motion, thus eliminating the problem of the SkHE associated with skyrmions. Skyrmioniums have been suggested as potential candidates for diverse applications in spintronic devices owing to their unique motion characteristics and stability. They could function as information carriers in racetrack memory, where their ability to move along a straight line would be a significant advantage over skyrmions [14]. In addition, because of their topological protection, skyrmioniums exhibit a high degree of dependability in the presence of defects and noise making them a suitable candidate for magnetic storage and logic devices that require low energy consumption and high density.

While skyrmions and skyrmioniums have shown promising potential in the field of spintronics, it is crucial to consider the real-world scenarios where these structures will operate. In practical applications, materials often contain defects that can

influence the behaviour of these topological entities. These defects can range from atomic scale irregularities to larger scale inhomogeneities.

The interaction between skyrmions or skyrmioniums and these defects can significantly affect their stability and motion characteristics. For instance, defects can act as pinning sites that impede the motion of skyrmions, affecting their trajectory and speed. On the other hand, skyrmioniums and skyrmions, due to their topological protection and unique motion characteristics, exhibit a high degree of dependability in the presence of defects and noise. This makes them a suitable candidate for magnetic storage and logic devices that require low energy consumption and high density.

Recent studies have explored the impact of these defect on skyrmion and skyrmionium dynamics [15–24]. The work referenced in [20] investigated the interaction of skyrmions with antidot lattices. They found that skyrmions are stabilized near the bottom of valleys formed by the antidot lattice, and sufficient spin torque is required to move the skyrmions over the energy barrier from one valley to another. They showed that the skyrmion hall effect can be effectively eliminated by using larger current values with shorter pulse duration which makes the skyrmion move from one valley to the other in the direction of the applied current pulse. Additionally, they found that skyrmions can be moved to any lattice point by carefully choosing material, current and antidot lattice parameters. The study concluded that the antidot lattice can be used as a medium for well-controlled skyrmion motion, which is an important step towards skyrmion-based devices [20].

The research referenced in [22] explored the interaction of skyrmions with granular films. Their study focuses on the motion of skyrmions in a polycrystalline sample, where the skyrmion trajectory is influenced by the grain boundaries of the material. At low current densities, the skyrmions exhibit a sliding motion along the grain boundaries, leading to pinning at the grain junctions. However, as the current density increases, the skyrmions become less sensitive to the grain boundaries, reducing the sliding motion, and making the overall trajectory of the skyrmions straighter, thereby reducing the overall skyrmion Hall effect. The researchers also discuss the influence of the nonadiabaticity parameter on the critical driving velocity. The nonadiabaticity parameter governs the longitudinal motion of skyrmions and drives the transverse velocity when it is not equal to the damping parameter. Increasing the nonadiabaticity results in the decrease of pinning phenomena since nonadiabaticity parameter drives the skyrmion out of sliding motion. The study also presents a model

to explain the skyrmion trajectory when the average grain size is much larger than the skyrmion size. In this case, the skyrmion speeds up along the grain boundary and most likely leaves it before it reaches the junction, resulting in a low probability to get pinned, and a near disorder-free trajectory [22].

The work referenced in [17] investigated the dynamics of a magnetic skyrmionium driven by spin waves on a racetrack with vacancy defects. They reported that when this interaction occurs, three different modes (pinning, depinning, reflection) are possible, depending on the amplitude and frequency of the spin waves and the size of the defect. If the radius of the skyrmionium is equal or smaller than the defect, the skyrmionium is reflected along the direction of spin-waves. This is attributed to the competition between the driving force induced by spin waves and the potential well induced by defects. When the skyrmionium radius is larger than defect radius, the skyrmionium can be pinned in the at the defects. It can be depinned by increasing the driving force and overcoming the pinning potential of the defect. The results of this study provide insight into the interaction between the skyrmionium and defects [17].

In this thesis, an in-depth exploration of the nucleation of skyrmioniums and their subsequent interaction with engineered defects strategically placed on a magnetic racetrack is conducted. The nucleation process is initiated by the injection of two pulses of spin-polarized current, applied in opposite directions to a circular contact. This method has been found to be effective in creating stable skyrmionium structures, which are then positioned on a racetrack for further examination. Following the successful nucleation, an in-plane current is applied to propel the skyrmionium along the positive x-axis of the racetrack. This allows for the observation of the skyrmionium's motion and its response to various influences within the system. To investigate the interaction between the skyrmionium and potential defects within the material, a thickness perturbation is introduced along the skyrmionium's path. These perturbations, or engineered defects, are varied in terms of both depth and shape to provide a comprehensive understanding of how such defects may impact the skyrmionium's motion and stability. The study provides valuable insights into the behaviour of skyrmioniums in the presence of defects, which is crucial for the development of skyrmion-based devices. The findings from this research could have significant implications for the design and optimization of future spintronic devices, particularly those that leverage the unique properties of skyrmioniums.

2. THEORETICAL BACKGROUND

2.1. Magnetic Interactions

Understanding the intricate magnetic interactions within magnetic materials is fundamental to comprehend the emergence and stabilization of complex magnetic structures such as skyrmions. These magnetic interactions determine the dynamic properties of magnetic spins and, consequently, govern the states of magnetism observed in various materials. In this context, skyrmions, offer a fascinating case study, as their existence and stability hinge on a delicate balance between different magnetic interactions, including the exchange interaction, the Dzyaloshinskii-Moriya interaction (DMI), the Zeeman interaction, and the magneto crystalline anisotropy. In the following sections, we will discuss these interactions in detail, emphasizing their roles and interplay in facilitating the formation and stabilization of skyrmions, as well as the conditions under which they enable these unique topological entities to arise and persist.

2.1.1 Exchange Interaction

The Heisenberg exchange interaction is a fundamental concept in the field of magnetism that describes the tendency of electron spins in neighbouring atoms to align with one another. This interaction plays a crucial role in determining the magnetic properties of a material.

Ferromagnetic materials have an exchange interaction, which is a quantum mechanical effect where localised spins prefer a parallel arrangement over an antiparallel one. This gives the material a net magnetization even without an external field. The inclination towards parallel spin alignment is due to the reduced Coulomb energy expectation value, which is a result of the increased expectation value of distance in a two-particle system (typically involving two electrons) when their spins are parallel. The origin of the exchange interaction lies in the Pauli exclusion principle which states that no two fermions in the same atom can have the same quantum states at the same time. Let us consider a system where there are only two electrons, like hydrogen. The first electron is in the state $\psi_a(r_1)$, and the second electron in the state

$\psi_b(r_2)$. The system's overall wave function is subject to the principles of exchange symmetry, thereby limiting the allowable states to either symmetric or antisymmetric forms. Due to the Pauli exclusion principle the overall wave function must be antisymmetric. Consequently, the spin part of the wave function is either in a singlet state χ_S (antisymmetric) or in a triplet state χ_T (symmetric) [25]:

$$\begin{aligned}\Psi_S &= \frac{1}{\sqrt{2}} [\psi_a(r_1)\psi_b(r_2) + \psi_a(r_2)\psi_b(r_1)]\chi_S \\ \Psi_T &= \frac{1}{\sqrt{2}} [\psi_a(r_1)\psi_b(r_2) - \psi_a(r_2)\psi_b(r_1)]\chi_T\end{aligned}\quad (2.1)$$

The energies of these state are:

$$\begin{aligned}E_S &= \int \Psi_S^* \hat{H} \Psi_S dr_1 dr_2 \\ E_T &= \int \Psi_T^* \hat{H} \Psi_T dr_1 dr_2\end{aligned}\quad (2.2)$$

The difference between the energies is:

$$E_S - E_T = 2 \int \psi_a^*(r_1)\psi_b^*(r_2) \hat{H} \psi_a(r_2)\psi_b(r_1) dr_1 dr_2 \quad (2.3)$$

The spin term of effective Hamiltonian, using the relation between the spin states, can be written as:

$$\hat{H}^{spin} = -2JS_1 \cdot S_2 \quad (2.4)$$

Where J is the exchange integral, and it is defined by $J = (E_S - E_T)/2$. If $J > 0$, then $E_S > E_T$ and the ferromagnetic state is favoured. If $J < 0$, then $E_S < E_T$ and the antiferromagnetic state is favoured [26].

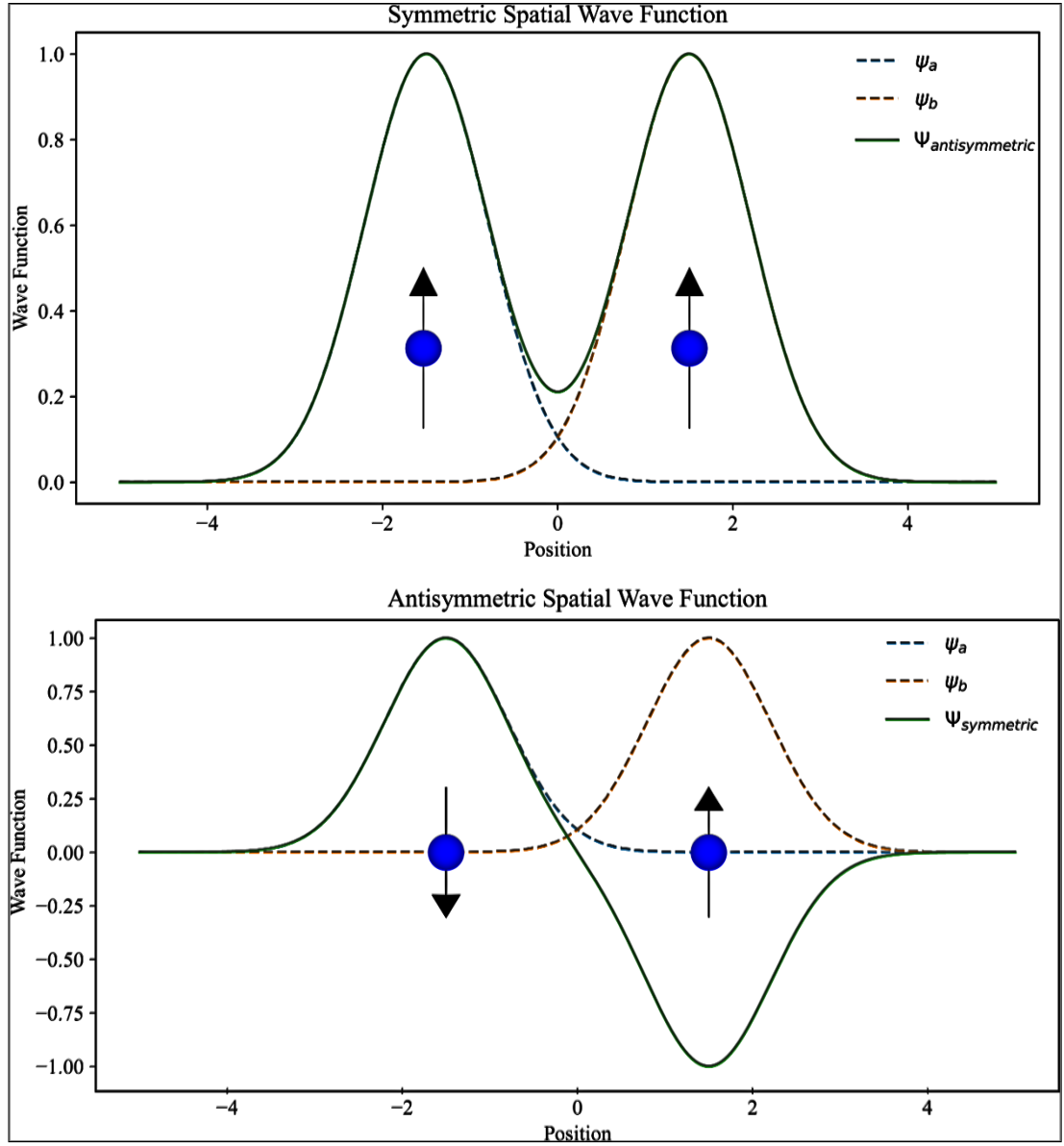


Figure 2.1: Visualization of exchange interaction in magnetic materials. The blue circles represent electrons, and the black arrows represent their spins.

2.1.2 Dzyaloshinskii-Moriya Interaction

Dzyaloshinskii-Moriya Interaction (DMI), also known as the antisymmetric exchange, is a unique type of exchange interaction that plays a pivotal role in the formation of complex magnetic structures such as skyrmions. This interaction was first postulated by Igor Dzyaloshinskii to explain the weak ferromagnetism observed in materials that are generally antiferromagnetic [4]. Dzyaloshinskii proposed that in certain circumstances, there exists a unidirectional, chiral component to the standard

Heisenberg exchange interaction. This phenomenon is described by an additional term in the Hamiltonian, which takes the form:

$$\hat{\mathcal{H}}^{DM} = D \mathbf{S}_1 \times \mathbf{S}_2 \quad (2.5)$$

where D is the Dzyaloshinskii vector and $\mathbf{S}_1$ and $\mathbf{S}_2$ are the spins of neighbouring atoms. The nature of this interaction allows it to induce a configuration where $\mathbf{S}_1$ and $\mathbf{S}_2$ are positioned orthogonally in a plane that is perpendicular to the vector D . This arrangement is favoured due to the negative energy associated with it. Consequently, its impact frequently results in canting of the spins. Toru Moriya's research has built upon the work of Dzyaloshinskii, by suggesting that this interaction is a result of spin-orbit coupling in the presence of super exchange interactions, which are mediated by non-magnetic atoms. [5]. In systems that lack inversion symmetry, the spin-orbit interaction can generate a Hamiltonian term that incorporates the DMI, which imparts a unique chiral nature to the magnetic configuration. Moriya proposed a collection of symmetry rules to anticipate the orientation of the Dzyaloshinskii vectors. The rules are given at figure.

2.1.3. Magnetocrystalline Anisotropy

Magnetocrystalline anisotropy is a property of magnetic materials where certain crystallographic directions are easier to magnetize than others. It is, fundamentally a result of the interplay between spin-orbit interaction and crystallographic structure of the material. This interplay compels electron spins to align along specific crystallographic axis which results in preferential orientations for the magnetic moment, also known as easy magnetization axis. Deviating from these preferred directions imposes an additional energy cost to the system, leading to the emergence of anisotropy energy [27,28]. For hexagonal crystals the energy density term is:

$$E = K_1 \sin^2 \theta + K_2 \sin^4 \theta + K_3 \sin^6 \theta \cos 6\varphi \quad (2.6)$$

Where θ is the c axis of the hexagonal plane and the magnetization vector, φ is the angle between the projection of the magnetization vector in the basal plane of the

crystal and one of the “a” axis. K_1 , K_2 and K_3 are the first, second and third order anisotropy constant, respectively given J/m^3 . The magnitudes of the anisotropy constants K_1 , K_2 and K_3 determines the strength of the anisotropy energy.

2.1.4 Zeeman Energy

The Zeeman energy refers to the additional potential energy experienced by a magnetic moment when it is placed in an external magnetic field. It is named after the Dutch physicist Pieter Zeeman, who discovered this effect and was awarded the Nobel Prize in Physics in 1902 for his work [29]. It is given by the following equation:

$$E_{Zeeman} = -\mu_0 \int_V \mathbf{M} \cdot \mathbf{H}_{ext} dV \quad (2.7)$$

Where H_{ext} is the external field, M is the magnetisation under the external field. The negative sign in the equation indicates that the energy is lower (more favourable) when the magnetic moment and the magnetic field are aligned. The Zeeman energy plays a vital role in many areas of physics, including atomic physics, nuclear magnetic resonance (NMR) [30], electron spin resonance (ESR), and magnetic resonance imaging (MRI) [31]. It is also essential in understanding the behaviour of magnetic materials in an external magnetic field, where the balance between Zeeman energy and other forms of magnetic energy, such as exchange energy and magnetocrystalline anisotropy energy, dictates the overall magnetic behaviour of the system.

2.1.5. Magnetic Skyrmion and Skyrmioniums

A magnetic skyrmion is a spin configuration that is characterized by a steady rotation of spins from one edge to the other. They exist in two primary forms: Bloch-type and Néel-type skyrmions. The emergence of discrete classifications can be attributed to variations in spin interactions, which are influenced by either the intrinsic crystal lattice arrangement or the existence of an interface. The spin configuration of skyrmions is commonly determined by the Dzyaloshinskii-Moriya interactions (DMI), which play a critical role in conferring a unique chirality to these entities. The

characteristic of chirality is a distinctive attribute of skyrmions that sets them apart from other types of local, swirling magnetic textures, such as magnetic bubbles. It is noteworthy that magnetic bubbles can persist even in the absence of DMIs. The phenomenon of chirality in skyrmions results in a significant topological aspect, which confers stability and protection due to the presence of a topological barrier [32]. This barrier is characterized by the skyrmion number otherwise known as topological charge or winding number and it is given by the following equation [33]:

$$N_{sk} = \frac{1}{4\pi} \int m \cdot \left[\frac{\partial m}{\partial x} \times \frac{\partial m}{\partial y} \right] d^2r \quad (2.8)$$

When the spins that form a skyrmion completely wrap a sphere, they yield a skyrmion number (N_{sk}) that takes the values of +1 or -1, dependent on the direction of the wrapping. The topological protection stems from this phenomenon. This protection implies the necessity of a specific energy input to destabilize a skyrmion. Simultaneously, due to this protection, skyrmions can facilitate reversible transitions between structures possessing the same topological number, contributing to their versatile nature. The particle-like nature of skyrmions is a crucial aspect that enables them to interact with currents and move dynamically [34]. The exploitable nature of this property renders it suitable for employment in diverse applications within devices.

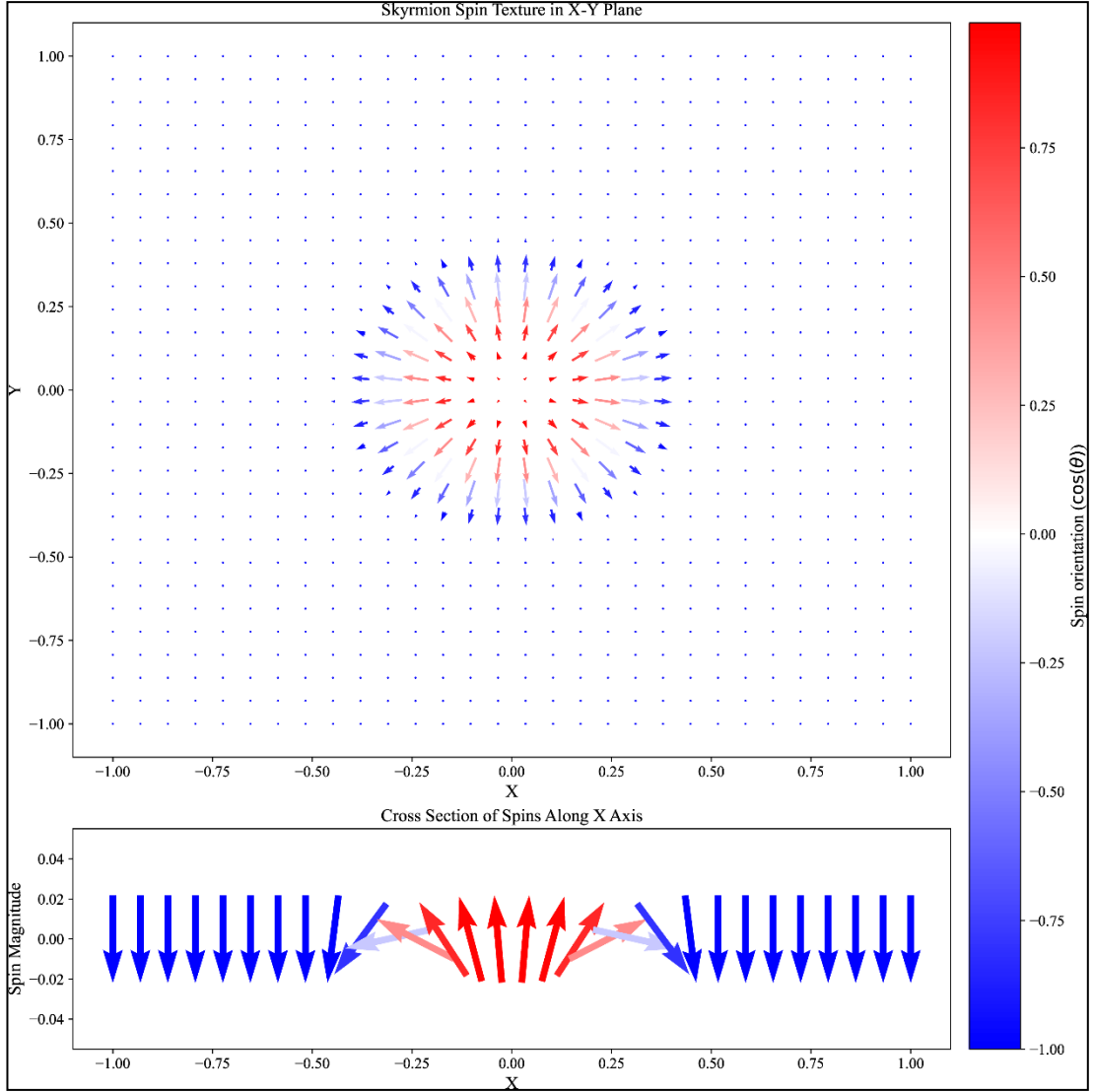


Figure 2.2: Visualization of a magnetic skyrmion. The top panel shows the spin texture in the X-Y plane, where the arrows represent the direction of the spins. The colour of the arrows indicates the spin orientation along the Z-axis. The bottom panel presents a cross-section of spins along the X-axis.

Skyrmions were first observed in magnetic compounds with a non-centrosymmetric lattice structure, with spin-orbit coupling induced DMIs. Subsequently, they were also detected in ultrathin magnetic films deposited on heavy metals, which are prone to DMIs because of the inversion symmetry disruption at the interface and the robust spin-orbit coupling of the neighbouring heavy metal [32].

A promising avenue for the application of skyrmions involves the advancement of multilayer structures with perpendicular magnetization, which can leverage the cumulative effect of Dzyaloshinskii-Moriya interaction (DMI) at successive interfaces. Recent advancements in this field have led to the successful stabilisation of

skyrmions at ambient temperature, as well as their manipulation, creation, and displacement through the application of electrical current. The utilisation of topology, chiral interactions, and spin-orbit torques for potential technological applications represents a noteworthy progression in the realm of topological spintronics. Experimental observation of skyrmion motion through spin torques were first observed in MnSi [35] and FeGe [36]. A spin torque can be applied to a skyrmion in two ways. It can either be applied by injecting an in-plane spin polarized current (STT) to a ferromagnetic film or, in bilayer structures, by injecting a spin polarized current to a heavy metal layer which in turn, due to the spin hall effect, will generate a vertical pure spin current (SOT). In this thesis, we will primarily use SOT for the motion of skyrmions.

The motion of skyrmions, induced by SOT, can be described by using a modified version of the Thiele equation [37]:

$$-4\pi N_{sk} b e_z \times v - \alpha D b \cdot v - B I j = \nabla U(r) \quad (2.9)$$

Where N_{sk} is the skyrmion winding number, D is the dissipative tensor given by $D_{ij} = \int \partial_i m(r) \cdot \partial_j m(r) d^2r$ where $D_{xx} = D_{yy} = D = \pi^2 R_{sk}/\Delta$. Here R_{sk} is the skyrmion radius and Δ is the domain wall width given by $\Delta = \sqrt{(A/K_{eff})}$. The torque tensor I is given by $I_{ij} = \int [\partial_i m(r) \times \partial_j m(r)] d^2r$. This tensor describes the interaction between the injected spin s and the magnetic texture. The constants are $B = (\frac{\hbar}{2e}) \Theta_{sh}$ where Θ_{sh} is the spin hall angle and $b = (M_s/d_z) \gamma_e$ where M_s is the saturation magnetization, d_z is the thickness of the ferromagnetic layer and γ_e is the gyromagnetic ratio. $\nabla U(r)$ represents the potentials that can counteract to the motion of the skyrmion like pinning sites. The first term in the Thiele equation signifies the Magnus Force, which causes a lateral displacement of the skyrmion in relation to the applied current. This term bears resemblance to the Lorentz force observed in electric charges, leading to a phenomenon analogous to the Hall Effect. In the context of skyrmions, this is known as the Skyrmion Hall Effect (SkHE). The SkHE results from the topological nature of skyrmions and leads to a transverse motion in a direction perpendicular to the current flow. This unique behaviour, while holding potential for novel applications, also brings challenges due to the resulting deviations from intended paths.

Consider a scenario where a spin-polarized current density is applied along the x-axis of a ferromagnetic film, and there is no pinning effect ($\nabla U(r) = 0$). Solving the Thiele equation under these conditions will result in velocity values along the x and y axes. These values are $V_x = \left(-\frac{\alpha D}{N_{sk}^2 + \alpha^2 D^2}\right) B j_x$ and $V_y = \left(\frac{N_{sk}}{N_{sk}^2 + \alpha^2 D^2}\right)$. Ratio of the V_y and V_x gives:

$$\frac{V_y}{V_x} = \frac{-N_{sk}}{\alpha D} \quad (2.10)$$

The skyrmion hall angle is given by $\theta_{sk} = \tan^{-1} V_y/V_x$ which is independent from the applied current if there are no pinning effects present.

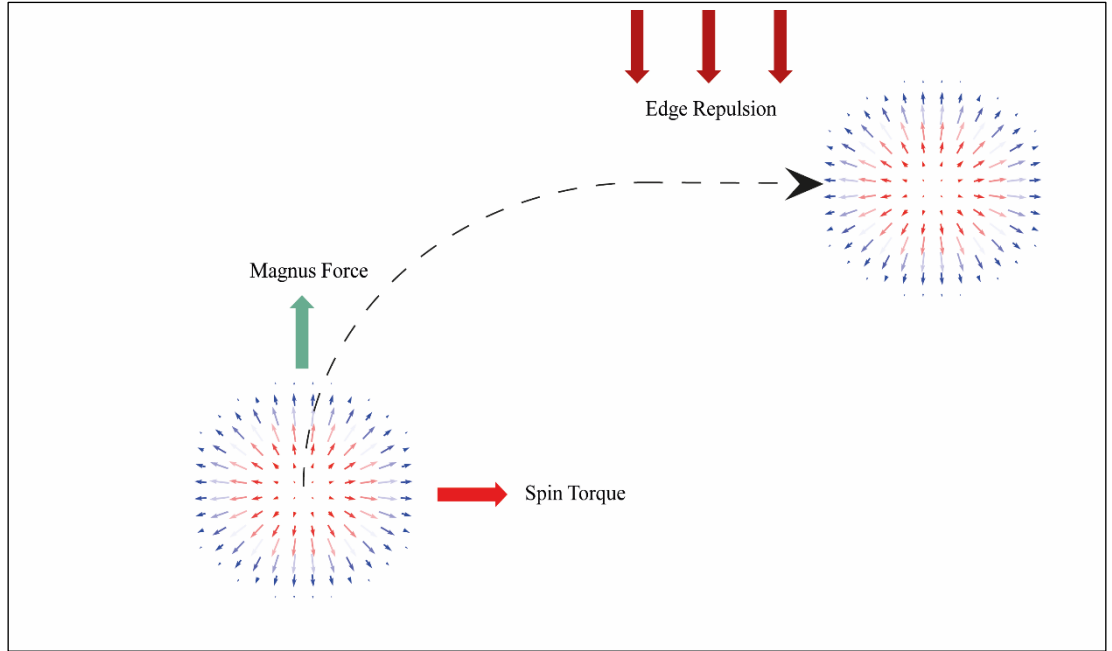


Figure 2.3: Visualization of the Skymion Hall Effect. The arrows inside the skyrmions represent the spin orientation, transitioning from blue (+z direction) at the core to red (-z direction) at the periphery.

The Skymion Hall Effect presents a unique set of challenges for the application of skyrmions in spintronic devices. Firstly, the transverse motion of skyrmions relative to the applied current due to the Skymion Hall Effect can cause them to deviate from their intended paths, potentially leading to loss of skyrmions at the edges of devices, which can disrupt their function [38]. This deviation could also increase the risk of collisions and unwanted interactions between skyrmions, particularly in dense

systems, which could affect the reliable reading or writing of information in spintronic devices.

A multitude of strategies have been deployed to counteract or mitigate the Skyrmion Hall Effect. The use of materials with certain symmetry properties, such as those found in antiferromagnetic materials, has been found to potentially eliminate SkHE [39]. Constrictions and other geometric modifications could guide skyrmions along intended paths, reducing SkHE. This includes the utilization of skyrmion channels or specially designed tracks that can direct the motion of skyrmions [7,40].

The solution we will focus on this thesis is using skyrmioniums instead of skyrmions [12]. A skyrmionium consists of a skyrmion surrounded by a ring-like circular domain wall with an opposing topological charge to the skyrmion [11]. It can also be considered as two concentric skyrmions with opposing topological charges. Due to the opposing topological charges of these concentric skyrmions, the net charge of a skyrmionium is $N_{sk}=0$. Like the skyrmions, skyrmionium can be driven by spin polarized current and be used as information carriers [41–44]. Due to having zero net topological charge, the first term in the Thiele equation vanishes for skyrmionium which means it doesn't experience a transverse motion when driven by a current. Like the skyrmion, skyrmionium can be used spintronic application. However, it's also worth noting that while skyrmioniums don't experience SkHE, they are generally more difficult to create and manipulate compared to skyrmions due to their complex spin structure and the requirement for specific material parameters and conditions.

In realistic material systems, the presence of defects such as lattice distortions, grain boundaries, and impurities can significantly affect the motion of both skyrmions and skyrmioniums, in addition to the SkHE. While recent studies have explored the impact of these defects on skyrmion dynamics [15–24] research on the interaction between skyrmioniums and material defects remains limited, with only a few studies addressing this topic [17,24]. A more comprehensive understanding of their dynamics in the presence of material defects is necessary for the design of skyrmion-based devices.

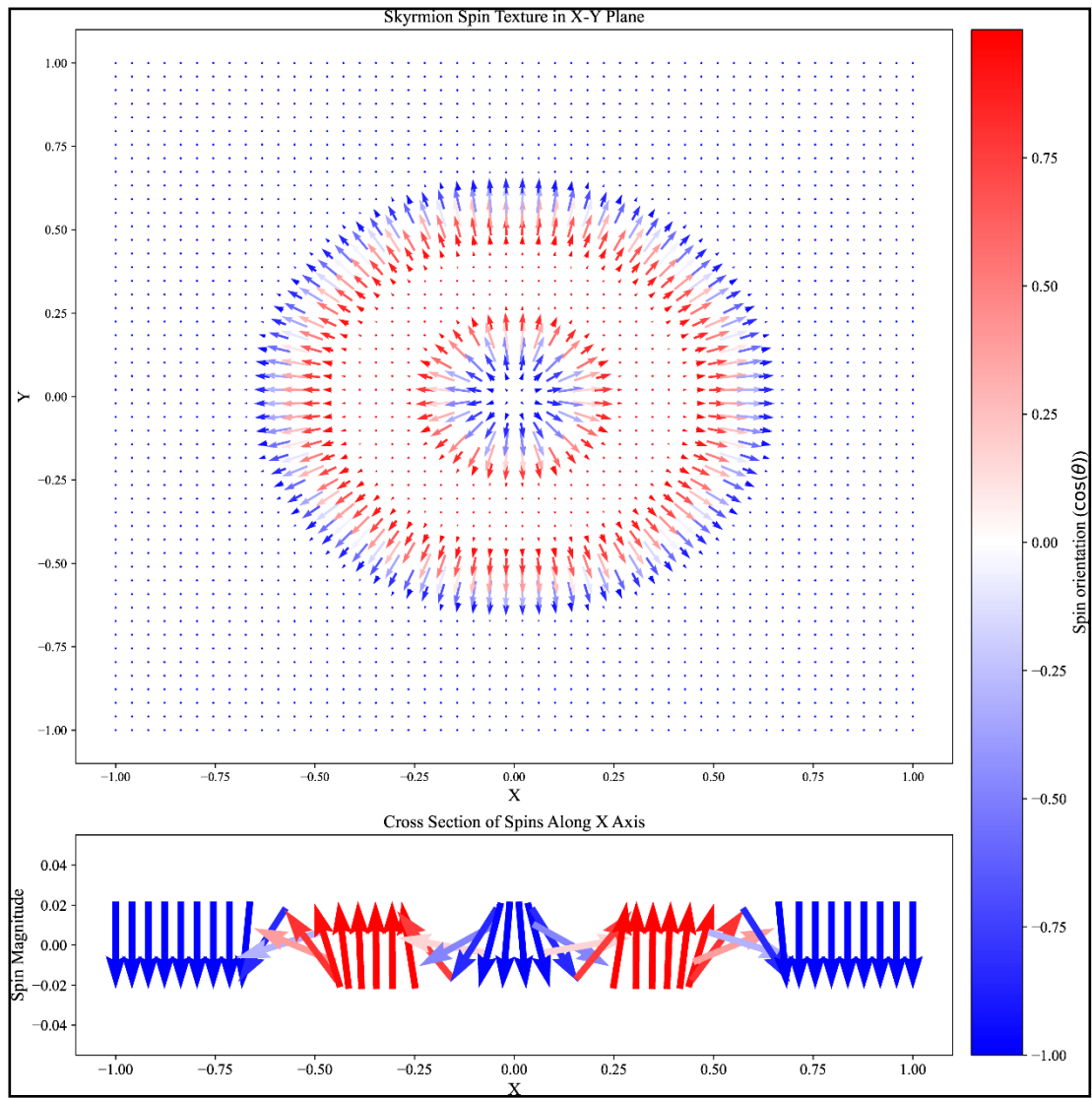


Figure 2.4: Visualization of a magnetic skyrmionium. The top panel displays the spin texture in the X-Y plane. Each arrow represents the direction of the spins. The bottom panel shows a cross-section of spins along the X-axis.

3. METHODS

3.1 Micromagnetic Framework

Micromagnetics is a field of magnetism that studies the magnetization of materials at microscale. It uses a continuous description of the magnetization $M(\mathbf{r})$ as a vector field but with constant module M_s to understand and predict various phenomena, including domain structure, domain wall motion, and skyrmion dynamics. Here M_s is the saturation magnetization, and it is described as the total magnetic moment per unit volume. The magnetization dynamics are often described by the Landau-Lifshitz-Gilbert (LLG) equation [45]. The LLG equation models how the magnetization vector evolves over time under the influence of an applied magnetic field and other internal forces. In the simulation presented in this thesis, we use software packages MuMax3 [46] and Boris Computational Spintronics [47] which utilizes micromagnetic framework to find the stable magnetization configuration and to observe the dynamics of the magnetization in an effective field.

A stable magnetization configuration is obtained by finding the local minima of the free energy E of the system with respect to its magnetization $\mathbf{m} = M(\mathbf{r})/M_s$. The free energy of a material is dependent on several phenomena related to magnetization. The total energy is given as [46]:

$$E_{tot} = E_{ex} + E_{ani} + E_{ext} + E_{dem} \quad (3.1)$$

E_{ex} is the energy due to exchange interactions which compel neighbouring spins to align with each other either parallel or anti-parallel. It plays a critical role in maintaining the alignment of adjacent spins and its origins are explained in section 2.1.1. Exchange energy is given as [46]:

$$E_{ex} = A_{ex}(\nabla \mathbf{m})^2 \quad (3.2)$$

Here A_{ex} is the exchange stiffness constant, and it is related to the exchange integral J .

E_{ex} also includes the energy due to the antisymmetric exchange, also known as Dzyaloshinskii-Moriya Interaction, that favours a type of non-collinear alignment of spins, leading to chiral structures like magnetic skyrmion. The origin of this energy is explained in section 2.1.2. Antisymmetric exchange energy is given as[46]:

$$E_{dm} = D_i(m_z \nabla \cdot m - (m \cdot \nabla)m_z) + D_b m \cdot (\nabla \times m) \quad (3.3)$$

Here D_i is the interfacial DMI constant, and D_b is the bulk DMI constant. Depending on the material in question either D_i or D_b is used.

E_{ani} is the energy resulting from magneto-crystalline anisotropy. It is expressed by the tendency of spins to orient itself along specific directions within a crystalline lattice, owing to the existence of lower energy states. In the case of uniaxial anisotropy, it is given as [46]:

$$E_{ani} = -K_{u1}(m \cdot e_z)^2 - K_{u2}(m \cdot e_z)^4 \quad (3.4)$$

E_{ext} is the energy resulting from external magnetic fields acting on the spins. It is given as [46]:

$$E_{ext} = -\mu_0 M_s m \cdot H_{external} \quad (3.5)$$

E_{dem} is the energy resulting from magnetostatic or dipole-dipole interactions, commonly referred to as the demagnetizing field energy, is dependent on the orientation and distance between spins. It is given as [46]:

$$E_{dem} = -\mu_0 M_s m \cdot H_{demag} \quad (3.6)$$

Here H_{demag} is the demagnetizing field, related to the magnetization through the demagnetizing tensor 'N' as follows:

$$H_{demag} = -N \cdot M \quad (3.7)$$

For simple shapes, the tensor N may be substituted with a scalar factor, commonly referred to as the demagnetizing factor. However, in materials with complex geometry, the tensor N is a crucial consideration as it accounts for both the shape and orientation of the material. The demagnetizing tensor is related to the distribution of the magnetic field produced by the magnetization within the material.

Considering all these contributions to the energy, the total energy is given by:

$$E_{tot} = [A_{ex}(\nabla m)^2 - \mu_0 M_s m \cdot H_{external} - \mu_0 M_s m \cdot H_{demag} - K_{u1}(m \cdot e_z)^2 + D_i(m_z \nabla \cdot m - (m \cdot \nabla)m_z) + D_b m \cdot (\nabla \times m)] \quad (3.8)$$

Building upon the fundamental concepts of micromagnetics and the total energy contributions, our focus now shifts towards one of the foundational equations in micromagnetic dynamics, the Landau-Lifshitz-Gilbert (LLG) equation. The LLG equation is a differential equation that describes the time evolution of the magnetization vector in a magnetic material. The LLG equation expresses the precessional motion and the damping of the magnetization vector under the influence of an effective magnetic field [45].

$$\frac{dm}{dt} = -\gamma m \times H_{eff} + \alpha(m \times \frac{dm}{dt}) \quad (3.9)$$

Here, m is the unit magnetization vector, γ is the gyromagnetic ratio, H_{eff} is the effective magnetic field, α is the Gilbert damping constant. The first term on the right-hand side represents the precession of the magnetization around the effective field, while the second term accounts for damping, which causes the magnetization to relax towards the direction of the effective field. The LLG equation signifies the dynamical response of the magnetization to the effective field. This response involves both a rapid precessional motion and a slower relaxation due to damping, which together determine the magnetization dynamics. The effective field is related to the total energy of the system, and it represents the force that drives the system to a state of lower energy. It can be written as:

$$H_{eff} = -\frac{1}{M_s V} \frac{\partial E_{tot}}{\partial m} \quad (3.10)$$

The LLG equation also includes the additional torques that can affect the spin dynamics of a system. The torque due to the spin-transfer torque (STT), also known as Zhang-Li STT is considered when a spin polarized current flows parallel to the magnetic layer surface [48]:

$$\tau_{ZL} = \frac{1}{1 + \alpha^2} [(1 + \xi\alpha)m \times (m \times (u \cdot \nabla)m) + (\xi - \alpha)m \times (u \cdot \nabla)m] \quad (3.11)$$

$$u = \frac{\mu_B \mu_0}{2e\gamma_0 B_{sat}(1 + \xi^2)} j \quad (3.12)$$

here ξ is the non-adiabaticity of the spin transfer torque, μ_B is the Bohr magneton, e is the charge of electrons and j is the current density vector.

The Slonczewski term or the spin-orbit torque term, enters the equation when a spin current is perpendicular to the magnetic layer surface. This current can enter from a neighbouring layer. The Slonczewski torque term is [49]:

$$\tau_{Sl} = \beta \frac{\epsilon - \alpha\epsilon'}{1 + \alpha^2} (m \times (m_p \times m)) - \beta \frac{\epsilon' - \alpha\epsilon}{1 + \alpha^2} m \times m_p \quad (3.13)$$

$$\beta = \frac{j_z \hbar}{M_s e d} \quad (3.14)$$

$$\epsilon = \frac{P(r, t)\Lambda^2}{(\Lambda^2 + 1) + (\Lambda^2 - 1)(m \cdot m_p)} \quad (3.15)$$

Here j_z is the current density along the z axis, d is the layer thickness, m_p is spin polarization of the neighbouring layer where the current enters the magnetic layer, P is the spin polarization of the current. λ and ϵ terms characterize the spacer layer and secondary spin torque parameters respectively.

Another torque term enters the equation when finite temperatures are considered. This term represents the random fluctuations in the effective magnetic field due to

thermal noise. According to Brown's model for thermal noise the fluctuating thermal field is given by [50]:

$$\vec{B}_{therm} = \vec{\eta}(step) \sqrt{\frac{2\mu_0\alpha k_B T}{B_{sat}\gamma_{LL}\Delta V\Delta t}} \quad (3.15)$$

where α is the dimensionless damping constant, k_B is the Boltzmann constant, T is the temperature, B_{sat} is the saturation magnetization given in Tesla, γ_{LL} is the gyromagnetic ratio, ΔV is the cell volume, Δt is the time step and $\vec{\eta}(step)$ is a random vector that changes its value after every time step. The cell volume ΔV is calculated during the simulation by multiplying cell sizes in each direction. When determining the value of the cell size we need to take in account the values of two parameters: width of the domain wall:

$$\delta = \sqrt{\frac{Aex}{K}} \quad (3.16)$$

and the exchange length:

$$l_{ex} = \sqrt{\frac{Aex}{0.5 * Msat^2 * \mu_0}} \quad (3.17)$$

To be able to resolve the smallest magnetic structure in the sample, one should choose roughly half the value of the smaller of the two parameters given above as cell size [51].

3.2 Experimental Techniques

3.2.1 X-Ray Reflectivity

X-Ray Reflectivity is a method where an X-Ray is sent onto a sample at very low angles to determine the parameters of the film grown onto the sample. These

parameters include thickness of the film, surface and interface roughness and the density of the film. This method can be applied to single-crystalline, polycrystalline, or amorphous materials and is not limited to evaluating diffraction phenomena. It is also capable of non-destructively evaluating surface roughness and interface width, studying an opaque film under visible light, and determining the layer structure of a multilayer or single-layer film.

In XRR, an X-ray beam is incident onto a sample surface at a grazing angle. If the angle is smaller than the critical angle for total reflection, total reflection occurs, and the incident X-rays do not penetrate the material. The X-ray reflectivity decreases rapidly with increasing incident angle above the critical angle. The ratio of reflected X-rays decreases proportionally to the fourth power of the incident angle.

The XRR measurement requires accurate sample alignment and the use of appropriate X-ray optics depending on the film thickness and sample size. The X-ray optics must be selected based on the film thickness. The analysis of XRR data provides information about the film thickness, density, and surface or interface roughness. The surface and interface roughness include physical unevenness and transitional boundary layers that continuously change in density [52].

3.2.2 Magnetron Sputtering

Magnetron sputtering is a widely used technique for the deposition of thin films. It is based on the principle of momentum exchange between ions and atoms. In this technique, a target material is bombarded with high-energy ions, which cause atoms from the target to be "sputtered" off and deposited onto a substrate. This process is enhanced using a magnetic field, which traps electrons near the target surface, leading to a higher ionization rate of the sputtering gas and thus a higher sputtering rate [53].

The magnetron sputtering process begins with the ionization of a neutral gas, such as argon, in the vicinity of the target material. The positively charged argon ions are then accelerated towards the negatively charged target. Upon impact, atoms from the target material are ejected, or sputtered, and then travel through the vacuum chamber to deposit onto the substrate.

A key feature of magnetron sputtering is the formation of a "racetrack" on the target surface. This is a region of enhanced sputtering rate caused by the interaction of

the magnetic and electric field lines. The sputtered material is eroded away from the target surface, creating a crater-like racetrack. This region is where most of the sputtering occurs.

Magnetron sputtering can be used to grow variety of different materials, like metals, semiconductors, and insulators. It can also be used to create compound coatings through a process known as reactive sputtering. In reactive sputtering, a reactive gas (such as oxygen, nitrogen, or a carbon-containing gas) is introduced into the sputtering chamber. The reactive gas reacts with the sputtered atoms to form a compound material on the substrate surface. This technique can be used to produce a variety of compound coatings, including nitrides, carbides, and oxides.

One variant of the magnetron sputtering technique is unbalanced magnetron sputtering. In this configuration, the strength of the magnets is varied, which changes the configuration of the magnetic field lines and results in a denser plasma near the target surface. This leads to an enhancement of the rate of sputtered ions leaving the surface and being accelerated towards the substrate. This can result in denser and harder coatings compared to conventional magnetron sputtering.

4. RESULTS

4.1 Nucleation Mechanism

In this section of the thesis, we will explain the nucleation process of skyrmions and skyrmioniums. Primarily, our focus is on the nucleation of skyrmioniums. However, during this study, we discovered that this process can also be applied to nucleate skyrmions and skyrmioniums with multiple outer rings which we call concentric skyrmions or skyrmioniums. The methodology and findings related to the formation of concentric structures will be presented alongside skyrmionium nucleation, while retaining an emphasis on the latter.

To nucleate a skyrmion, a spin-polarized current is applied perpendicularly to the in-plane interface through a vertical top circular contact at the uniformly magnetized interface of a heavy metal and a ferromagnetic bilayer thin film structure. This configuration results in anti-parallel alignment of the spins at the interface and spins in the polarized current along the z-axis, as depicted in Fig.1. The perpendicular spin-polarized current induces a reversal of the anti-parallel aligned spins in the contact area at the interface due to the spin-orbit torque effect, which leads to the formation of a skyrmion in the centre of the initially uniformly magnetized disk.

For simulations conducted at 0 Kelvin, the reversal throughout the contact area occurs instantaneously, with the resultant skyrmion being larger than the contact area where the current is applied. In temperature-dependent simulations, thermal energy barriers cause a gradual reversal of the spins under the contact. The process begins with the formation of one or more vortexes within the contact area, and as the constant current is applied, the reversed area expands. It eventually surpasses the size of the contact area.

Additionally, by applying the same perpendicular current but with an inverted spin polarization, it is possible to create a skyrmionium and spin structures with multiple outer rings of alternating spin alignments, as shown in Fig.1. This is achieved by satisfying the condition of anti-parallel spin alignment between the interface spins and the polarization of the applied current, in accordance with the spin-orbit torque effect. Altering the spin polarization of the perpendicular current relative to the central skyrmion, and cyclically repeating this pattern, results in the formation of additional

spin rings. The final configuration of the spin texture, including the number of rings and the size of the central skyrmion, is dependent on the meticulous adjustment of several parameters, such as the exchange energy between the spins at the interface, the density of the applied current, the duration for which the current is applied, the contact area, and the total area at the interface.

Our primary objective is to study the nucleation of stable skyrmioniums, for which we employed different material combinations, including Co/Pt [7] and $\text{Tm}_3\text{Fe}_5\text{O}_{12}/\text{Pt}$ [54]. We successfully nucleated and stabilized skyrmionium structures by carefully adjusting the applied current density and current pulse pattern for each material pair. The parameters utilized in our simulations were adapted from relevant literature with minimal alterations and are following the constraints of contemporary microfabrication techniques and experimental practicability. The material parameters for different combinations are presented in Table 1.

Table 4.1. Parameters for Co/Pt and $\text{Tm}_3\text{Fe}_5\text{O}_{12}/\text{Pt}$. Here K_u , M_s , A_{ex} , D_{ind} , and α refer to uniaxial anisotropy constant, saturation magnetization, exchange stiffness coefficient, interfacial Dzyaloshinskii-Moriya interaction constant and damping constant respectively.

Material Type	Material Name	K_u ($\text{kJ}\cdot\text{m}^{-3}$)	M_s ($\text{MA}\cdot\text{m}^{-1}$)	A_{ex} ($\text{pJ}\cdot\text{m}^{-1}$)	D_{ind} ($\text{mJ}\cdot\text{m}^{-2}$)	α
Ferromagnetic Metal/HM	Co/Pt	800	0.58	15	3.8	0.3
Ferrimagnetic Insulator/HM	TmIG/Pt	11.88	0.1	0.84	0.051	0.014

4.1.1. Nucleation Mechanism for Co/Pt

Figure 4.1a depicts the temporal evolution of the nucleation process for a concentric skyrmion at 300K within the Co/Pt interface. We modelled a disk with a thickness of 5 nm and a diameter of 300 nm, as illustrated in Fig.1a. The simulation initiates with a uniformly magnetized disk ($m_z=+1$, spin up) oriented in the +z-direction, possessing a net topological charge $N_{\text{sk}} = +1$. At $t=0$, a counter spin polarized current pulse ($m_z=-1$, spin down) with a density of $J = 7.6 \times 10^{12} \text{ A}\cdot\text{m}^{-2}$ is applied in the -z direction through a circular contact with a 100 nm diameter. This results in the

reversal of spins within the contact area due to the spin-orbit torque effect, giving rise to a skyrmion that subsequently expands beyond the contact area. As captured in snapshot no. 2 of Fig. 1a, the topological charge in this configuration becomes $N = -1$.

The current is sustained for 1 ns (Δt_1) to facilitate the growth of the skyrmion to a sufficient size to accommodate additional skyrmions with alternating spin alignments within the disk. It is essential to note that a skyrmion whose size is equivalent to or smaller than the contact area could be eliminated or reduced by the subsequent current pulse with inverted spin polarization. Moreover, the same current pulse, albeit with a reversed spin polarization, would produce another skyrmion at the centre, expanding it to a size like the initial skyrmion, ultimately reverting to the initial configuration of a uniformly magnetized disk in the +z direction.

To circumvent this, we modulate not only the spin polarization but also the density of the subsequent current pulse, reducing it to $J = 7.03 \times 10^{12} \text{ A}\cdot\text{m}^{-2}$. This pulse is applied for a duration of $\Delta t_2 = 1 \text{ ns}$ and engenders the creation of a second skyrmion with spins aligned in the +z direction. The ensuing structure, a skyrmionium, has a topological charge of $N = 0$, and is depicted in snapshot no. 3 of Fig. 1a.

Continuing in this vein—by inverting the polarization and further diminishing the current density to $J = 6.44 \times 10^{12} \text{ A}\cdot\text{m}^{-2}$ we induce the formation of another skyrmion at $t = 3 \text{ ns}$, yielding a skyrmionium with multiple regions of alternating spins and a net topological charge of $N_{\text{sk}} = -1$, as evident in snapshot no. 4 in Fig. 1a.

Subsequently, the applied current is discontinued, and the structure is allowed to evolve temporally to assess the stability of the skyrmionium up to $t = 12 \text{ ns}$, which marks the termination of the simulation. The stability is derived from the interplay between the radial demagnetizing field of the alternating rings and the central skyrmion, which is attributed to the circular geometry of the structure.

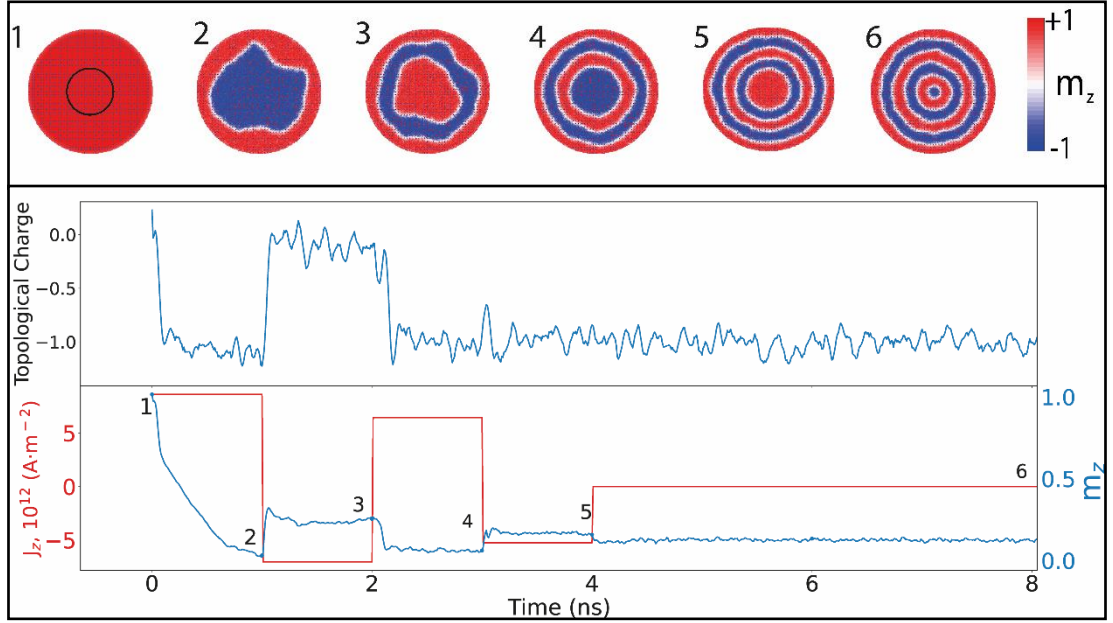


Figure 4.1: Current driven initialization and control of skyrmioniums and concentric skyrmions at room temperature for Co/Pt. (a) Time evolution of the system at current reversal points. Black circle in the snapshot no 1 shows the contact area. (b) Change of net topological charge with respect to time, applied spin polarized charge current density profile and change of perpendicular magnetization component m_z with time.

4.1.2 Nucleation Mechanism for TmIG/PT

Figure 4.2a presents the temporal evolution of the nucleation process for a concentric skyrmion at room temperature within the TmIG/Pt interface. The simulation employs a disk that is 24 nm thick and has a diameter of 1200 nm, which is four times larger than the disk used in the Co/Pt simulations. However, the contact area for the spin-polarized current remains consistent at 100 nm. This discrepancy in dimensions is attributed to the differing exchange lengths of the Co/Pt and TmIG/Pt stacks, resulting in simulation cell sizes of $1 \times 1 \times 1 \text{ nm}^3$ and $4 \times 4 \times 4 \text{ nm}^3$, respectively.

Mirroring the procedure adopted in the Co/Pt simulations, we begin with a disk uniformly magnetized along the $+z$ direction. The nucleation process for TmIG/Pt largely mirrors that of Co/Pt, except for variations in total pulse duration and current density values. At $t = 0$, a $-z$ polarized current with a density of $J = 4.8 \times 10^{11} \text{ A}\cdot\text{m}^{-2}$ is applied through a 100 nm circular contact for a duration of 1 ns (Δt_1). Subsequently, at $t = 1 \text{ ns}$, the current's polarization is inverted, and its density reduced to $J = 3 \times 10^{11} \text{ A}\cdot\text{m}^{-2}$. This altered pulse, maintained for 3 ns (Δt_2), culminates in the formation of a second skyrmion with spins aligned in the $+z$ direction. The extended pulse duration,

relative to Co/Pt, is necessitated by the lower current density. Additionally, skyrmions in TmIG/Pt interfaces exhibit prolonged relaxation times due to their lower damping value, as specified in Table 1.

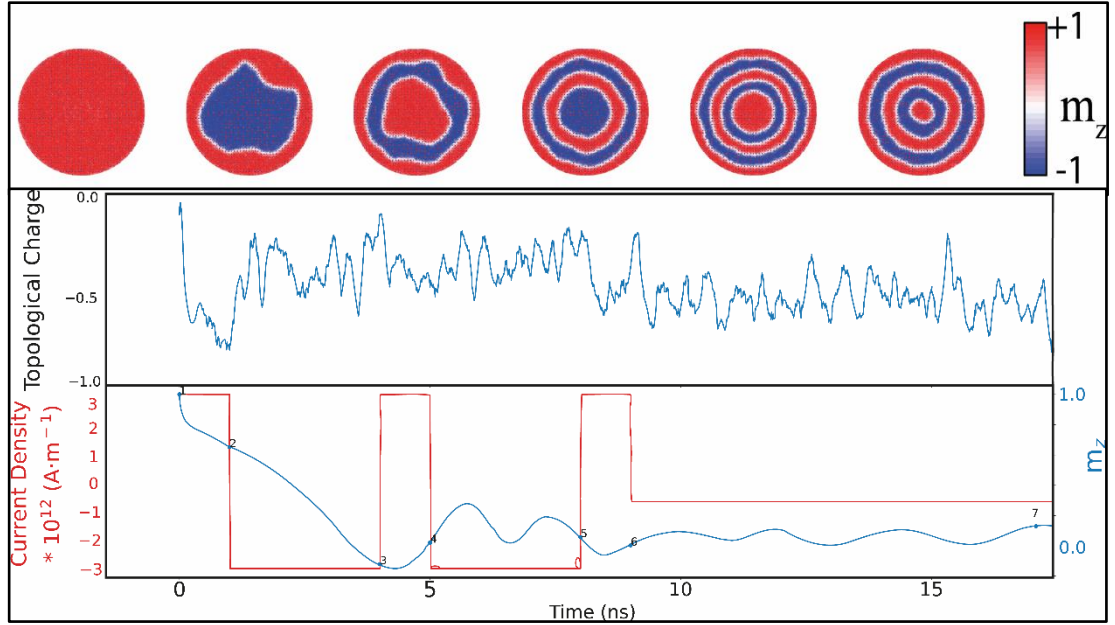


Figure 4.2: Current-driven initialization and control of skyrmioniums at room temperature for TmIG/Pt. (a) Time evolution of the system at current reversal points. (b) Applied spin-polarized charge current density profile and change of magnetization at z direction and topological charge with respect to time.

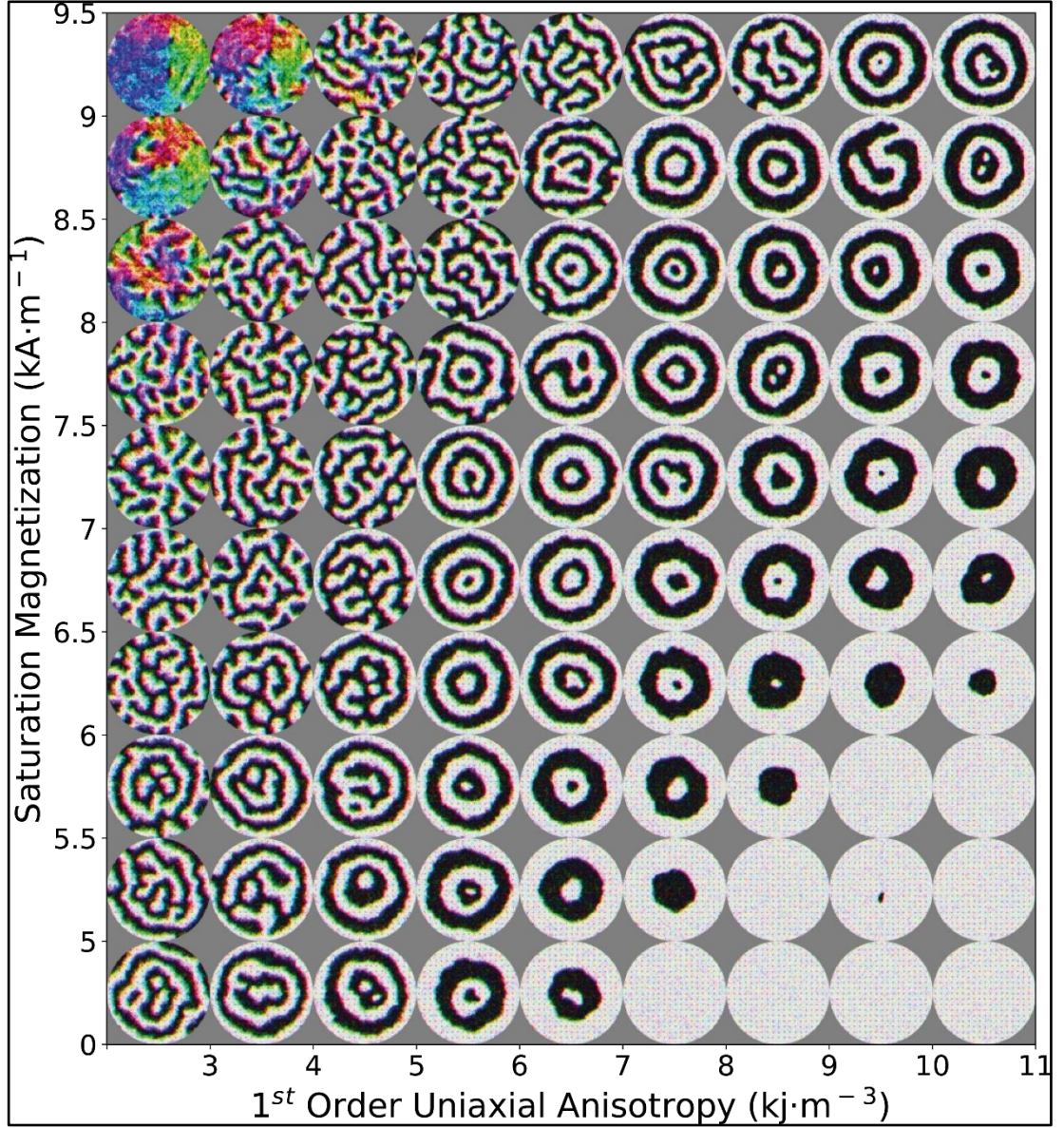


Figure 4.3: Phase diagram of skyrmionium nucleation process for different M_{sat} and K_u values.

At $t = 4$ ns, the spin polarization of the current is once again reversed, while the current density and pulse duration remain consistent with the initial step ($J = 4.8 \times 10^{11} \text{ A}\cdot\text{m}^{-2}$ and $\Delta t_1 = 1$ ns). The combination of the first and second steps constitutes a cycle that can be reiterated to generate additional skyrmion rings.

Figure 4.3 depicts a phase diagram of the nucleation process with varying values of K_u and M_{sat} , while keeping the current density profile fixed. The current density profile is illustrated in Figure 4.2b. Within the diagram, there exists a range of K_u and M_{sat} values conducive to the stabilization of concentric skyrmions. Within this region, skyrmion cases with topological numbers -1 and 0 can be manifested. It is noteworthy

that concentric skyrmions can also be nucleated outside this specific window by modifying the current density profile.

4.2 Spin Transfer Torque Driven Motion of Concentric Skyrmions

In this segment, our investigation focuses on the current-induced dynamics of three distinct types of concentric skyrmions on a magnetic racetrack for Co/Pt and TmIG/Pt materials. The simulation is based on a racetrack measuring $3000 \times 700 \times 5$ nm³. As illustrated in Fig 4.4, a concentric skyrmion, which has been previously nucleated, is positioned at the centre of the racetrack at $t = 0$ ns. Subsequently, a spin-polarized direct current is applied along the +x direction, with various density values, propelling the concentric skyrmion towards the left extremity of the racetrack. It is important to note that the magnetic parameters employed in simulating the motion of the concentric skyrmions remain consistent with those used in the nucleation process.

Figures 4.4b and c depict the relationship between the velocity of the concentric skyrmions and the density of the applied current for Co/Pt and TmIG/Pt materials. The threshold current necessary to initiate motion in a concentric skyrmion is as low as $J = 1.1 \times 10^{11}$ A·m⁻² for Co/Pt and $J = 1.0 \times 10^{10}$ A·m⁻² for TmIG/Pt. Across the board for all concentric skyrmions, there is a linear correlation between velocity and current density. Interestingly, within the range of current densities examined, the velocities of the concentric skyrmions appeared to be relatively uninfluenced by the number of rings. This observation leads to the inference that augmenting the number of rings can bolster the information density, and consequently, the transfer rate, without significantly impacting the velocity.

The discrepancy in velocities between Co/Pt and TmIG/Pt can be attributed to the simulation cell size employed for TmIG/Pt, which is quadruple that of Co/Pt. This essentially means that the TmIG/Pt racetrack possesses a thickness that is four times greater than that of the Co/Pt racetrack.

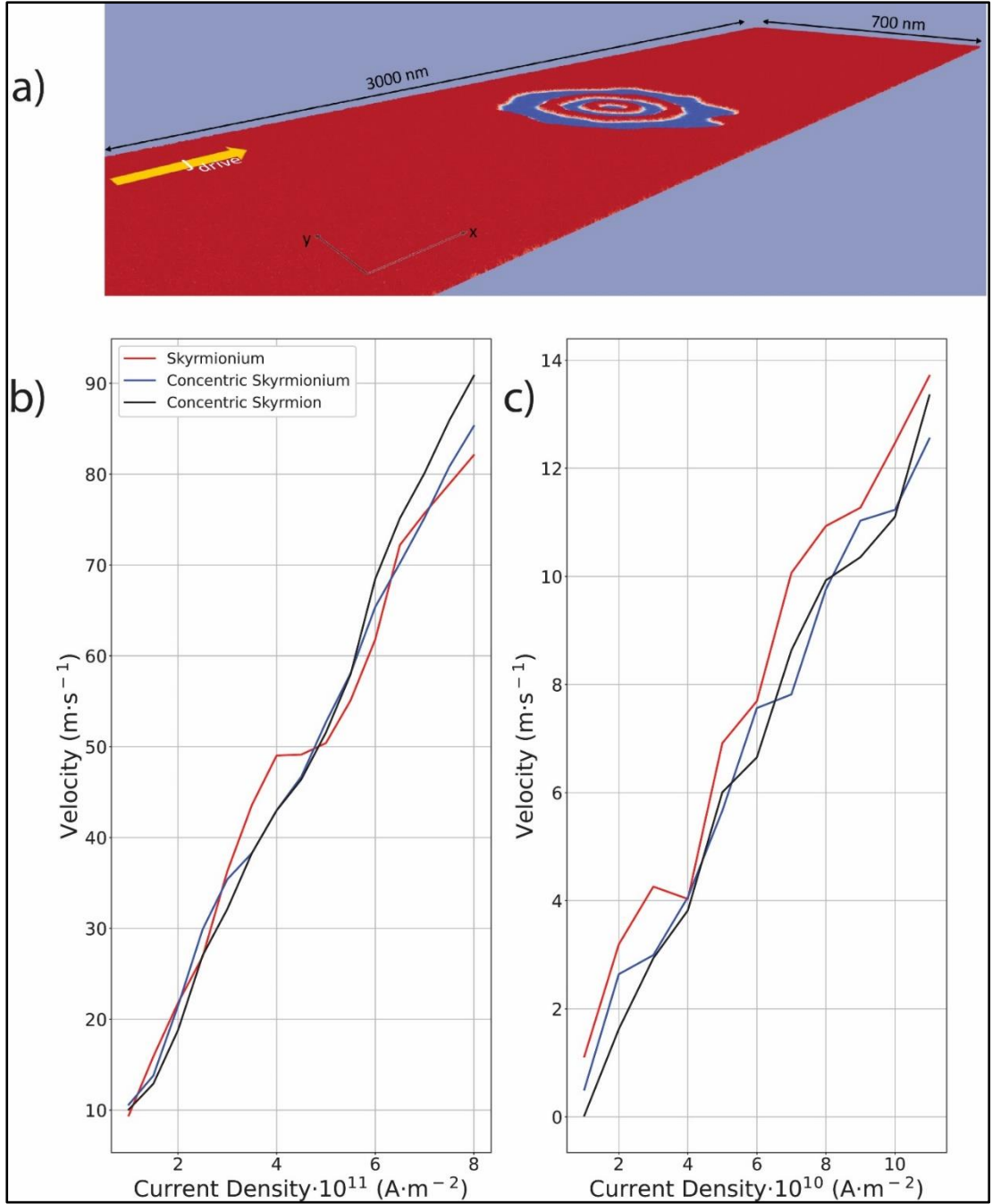


Figure 4.4: a) Illustration of the racetrack. Relation between velocity and current density for b) Co/Pt bilayer and c) TmIG/Pt bilayer.

4.3 Skyrmionium Interaction with Defects

Having explored the current-induced dynamics of concentric skyrmions on a magnetic racetrack, it's evident that they offer several advantages such as enhanced information density due to the presence of multiple ringed structures. However, when considering size and ease of manipulation, skyrmioniums emerge as an intriguing

alternative. Skyrmioniums are smaller in size compared to concentric skyrmions, which can be advantageous in certain applications, and they are easier to manipulate with currents. Moreover, skyrmioniums can be nucleated using a similar process to that of concentric skyrmions, albeit with fewer steps, making them potentially more efficient for certain applications.

Notably, there is limited research on the interaction of skyrmioniums with defects. Understanding this interaction is crucial, as real-world magnetic racetracks will invariably have imperfections that could affect the motion and stability of skyrmioniums. Thus, examining how skyrmioniums behave in the presence of defects is an essential step toward assessing their practicality for data storage and transfer applications.

In the following section, we delve into simulations conducted to analyse the interaction between a skyrmionium and defect in a ferromagnetic layer. This study aims to provide new insights into how skyrmioniums behave when subjected to electric currents and how they interact with defects on the racetrack. Such understanding is vital for optimizing the design and performance of magnetic racetrack memory devices that employ skyrmioniums.

To this end we conducted simulations on a ferromagnetic layer (shown in Figure 4.7) with a total volume of $1500 \times 150 \times 1 \text{ nm}^3$, which was divided into cells, each with a volume of $2 \times 2 \times 1 \text{ nm}^3$. The magnetic properties of the Co/Pt bilayer [7] were used, including saturation magnetization of $M_s = 580 \text{ kA} \cdot \text{m}^{-1}$, exchange stiffness of $A = 15 \text{ pJ} \cdot \text{m}^{-1}$, uniaxial anisotropy constant of $K = 0.8 \text{ MJ} \cdot \text{m}^{-3}$, and interfacial Dzyaloshinskii-Moriya interaction constant of $i\text{DMI} = 3.5 \text{ mJ} \cdot \text{m}^{-2}$. The spin hall angle was set to $\Theta_{sh} = 0.1$.

We used Boris Computational Spintronics software [39] to solve the Landau-Lifshitz-Gilbert (LLG) equation and model the motion of skyrmioniums on a surface with random and engineered defects. In the Boris computational software introducing disorder or surface roughness contributes an additional component to the effective magnetic field equation, termed B_{rough} . This additional term impacts the overall behaviour of the effective field. Taken together, these factors make the surface grains at the Co/Pt interface act like pinning points for skyrmion-like magnetic structures. The added height of the grains further influences the pinning of skyrmions.

Before starting our simulations, we performed experimental work to determine the average peak height of the interface roughness. We utilized X-ray Reflectivity

(XRR) to analyse the interface roughness of a multilayered sample. The sample was constructed by depositing layers of cobalt (Co), platinum (Pt), and tantalum (Ta) onto a silicon substrate. The thicknesses of the layers were carefully selected to align as closely as possible with our simulation values: the Pt layer was 10 nm, the Co layer was 1 nm, the Ta layer was 4 nm, and the capping layer of Pt was 1 nm. Following the growth of the sample, we conducted XRR measurements to evaluate the physical properties of the layers. The results from the XRR analysis were consistent with our initial layer thicknesses, confirming the accuracy of our deposition process.

However, the XRR data also revealed an unexpected finding. We observed that the Co layer had undergone oxidation, which led to an increase in the interface roughness value. Specifically, the interface roughness was found to be 0.5 nm, which exceeded our anticipated value of 0.3 nm. This discrepancy suggests that the oxidation of the Co layer contributed to a rougher interface than initially expected.

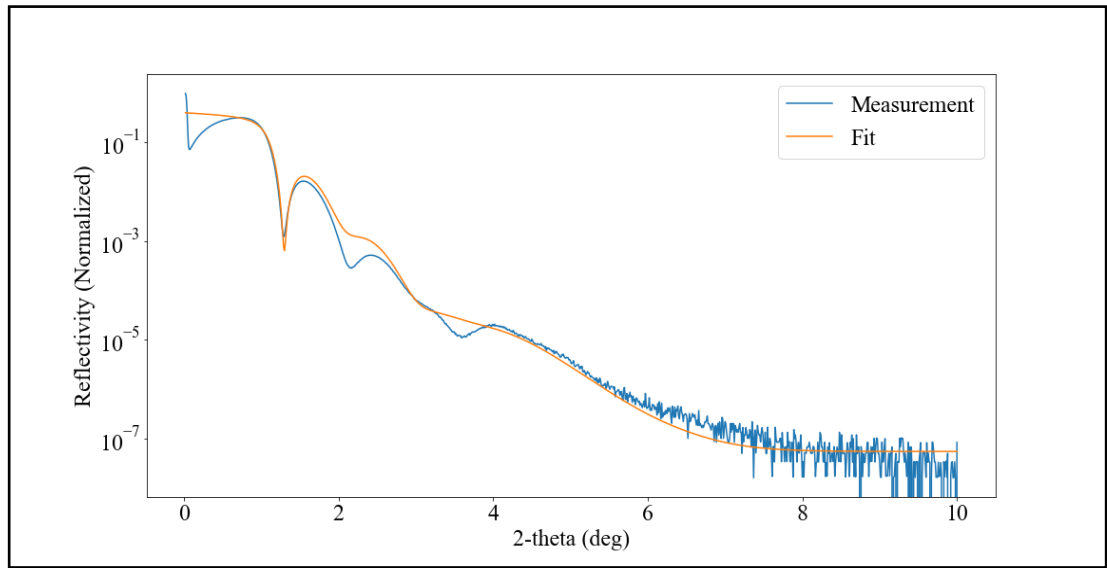


Figure 4.5: Results of the XRR measurement and the fitting graph to determine the thickness and the roughness of the films and the interface.

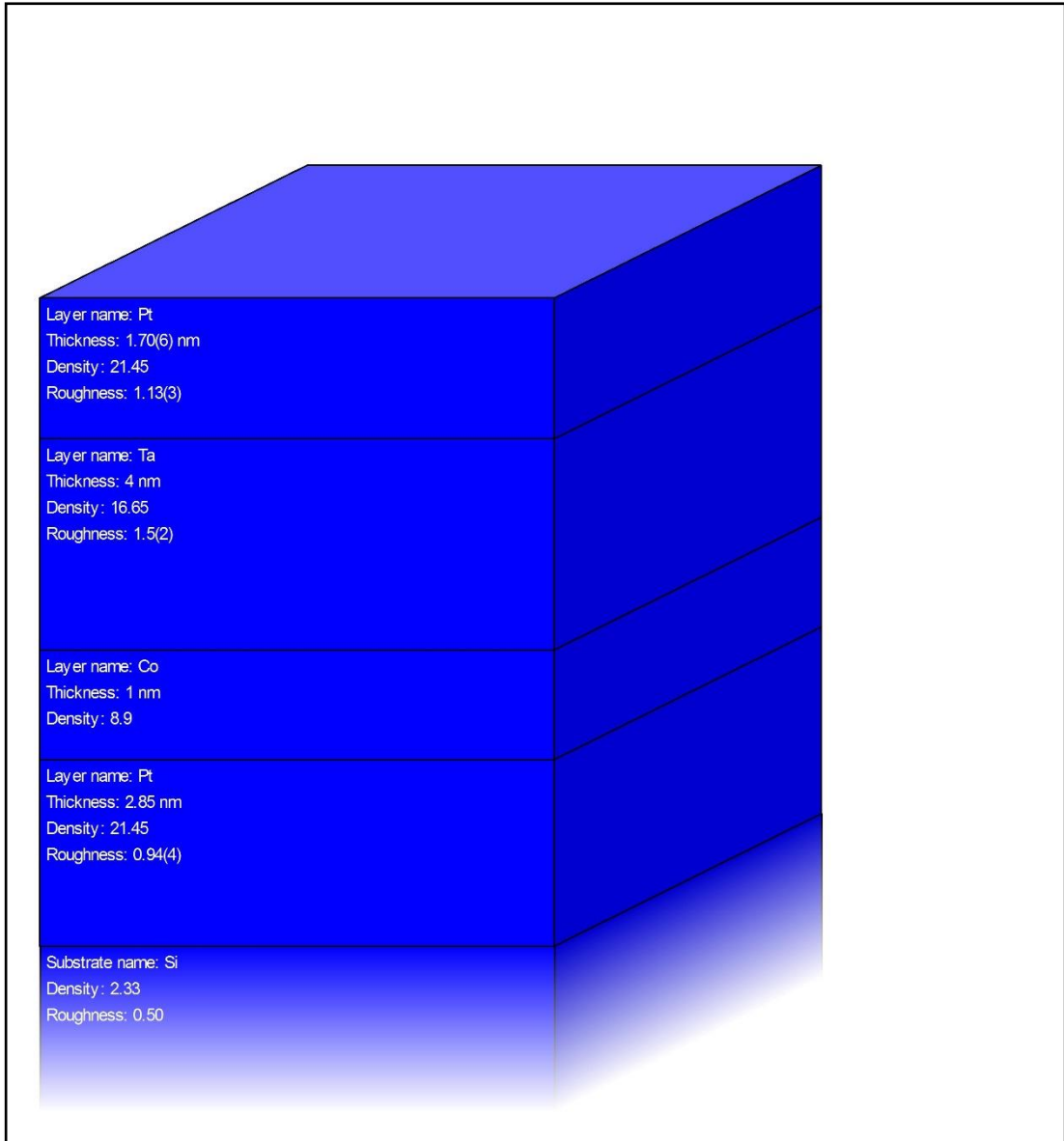


Figure 4.6: Film thickness and roughness sizes calculated from the XRR data.

Building upon our findings from the XRR analysis, particularly the observed interface roughness, we further explored the impact of surface roughness on the movement of skyrmionium. This led us to investigate the behaviour of skyrmionium as it traverses a surface characterized by random roughness. we maintained a constant grain size and distribution while systematically varying the grain height. We conducted simulations with grain heights ranging from 0.1 nm to 0.4 nm to observe the impact on the motion of the skyrmionium. Our results revealed that a grain height of 0.1 nm had minimal effect on the skyrmionium's motion. However, as we increased the grain height, the skyrmionium began to exhibit a "creeping" behaviour, moving from one

grain to another, transitioning between potential wells. This creeping motion became more pronounced with increasing grain height. At a height of 0.4 nm, the skyrmionium required a higher current density to move due to the increased pinning potential associated with the taller grains. Interestingly, we also observed a differential response between the inner and outer skyrmionium due to their energy difference. The inner skyrmionium, having lower energy, could become pinned at a grain, while the outer skyrmionium continued to move. This observation underscores the complex dynamics at play when navigating a surface characterized by variable grain heights.

After an extensive exploration of skyrmionium behaviour within a landscape of random roughness, we turn our attention towards its interaction with a distinctly different environment - one of engineered defects. Unlike the unpredictable and naturally occurring fluctuations seen in random roughness, engineered defects provide intentional and carefully planned changes to the material's structure. Our investigation now moves from the haphazardness of random surface features to the precision and control offered by engineered defects. This shift in focus promises to shed light on the influence of deliberate, controllable perturbations on skyrmionium behaviour. Such insights will be of considerable value when tailoring material properties for specific applications, particularly in the realm of spintronic devices where the precise manipulation of skyrmionium motion is crucial. In the following sections, we take a detailed look at the dynamics of a skyrmionium's interaction with individually placed defects, each exhibiting different characteristics. This part of the thesis has been published [55].

To study the interaction between a skyrmionium and the cylindrical defect, we placed a skyrmionium on the racetrack and allowed it to relax, resulting in a final stable diameter of $R_{sk} = 75$ nm. Then, an electric current was applied along the x-axis, causing the skyrmionium to move via spin orbit torque effect [56]. A cylindrical defect with a diameter of 120 nm and a depth of 0.3 nm was placed on the racetrack in the path of the skyrmionium. The purpose was to study the interaction between the skyrmionium and the defect. The grey area in Figure 4.7 represents the position and size of the defect.

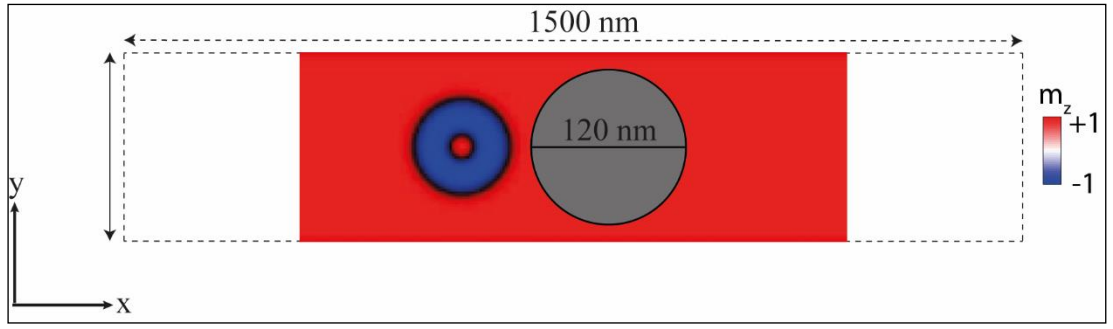


Figure 4.7: Racetrack geometry used in our simulations. Only a portion of the whole track is shown here. The dimensions of the racetrack are $1500 \times 150 \times 1$ nm³, length, width, and thickness, respectively. The grey area shows the position and size of the defect. The diameter and the depth of the defect is 120 nm and 0.3 nm respectively.

We started our investigation by analysing the 450 nm wide racetrack model. The results are given in Fig 4.9 (a-d). For the current density value $J = 150 \text{ GA} \cdot \text{m}^{-2}$ (Figure 4.9a), once the skyrmionium reaches the boundary of the defect, it begins to slide very slowly along the outer wall of the defect as the force exerted by the current is not strong enough to push skyrmionium inside. For $J = 200 \text{ GA} \cdot \text{m}^{-2}$ (Figure 4.9b) the skyrmionium partially enters the defect, becomes pinned on the defect wall, and starts moving along the wall until it gets depinned and exits. This process continues until $J = 450 \text{ GA} \cdot \text{m}^{-2}$ (Figure 4.9d) where the skyrmionium passes through the defect without sliding due to the increased driving force coming from the applied current density.

We continued our investigation by examining the 300 nm wide racetrack model. On this model, for $J = 150 \text{ GA} \cdot \text{m}^{-2}$ (Figure 4.9e) we observed that the skyrmionium slides on the defect's outer wall after it contacts it. For $J = 300 \text{ GA} \cdot \text{m}^{-2}$ a similar motion shown at Figure 4.9c can be seen. As the current density increased to $J = 375 \text{ GA} \cdot \text{m}^{-2}$, upon entering the defect, the skyrmionium was depinned from the inner wall after a very brief sliding motion due to the amplified force from the current. Once the skyrmionium is depinned, it moves towards the centre of the defect where it transforms into a skyrmion. After the transformation, the skyrmion starts moving at an angle of 60 degrees until it reaches the upper edge of the racetrack where it continues its motion horizontally. Further increasing the current density to $J = 450 \text{ GA} \cdot \text{m}^{-2}$ the skyrmionium passes through the defect without sliding on the defect wall.

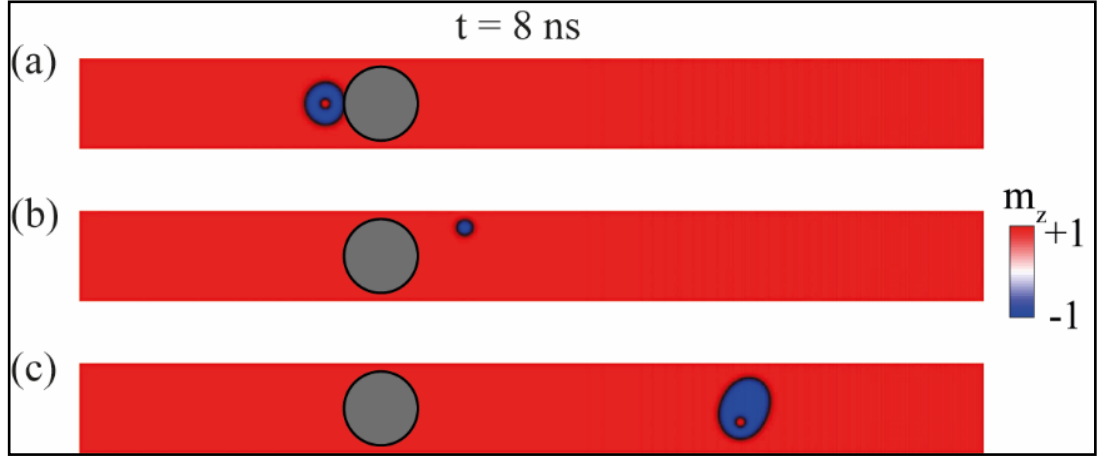


Figure 4.8: Final positions of skyrmioniums after 8 ns of current pulses of (a) $J = 150 \text{ GA} \cdot \text{m}^{-2}$, (b) $J = 300 \text{ GA} \cdot \text{m}^{-2}$ and (c) $J = 600 \text{ GA} \cdot \text{m}^{-2}$. The grey area represents the defect.

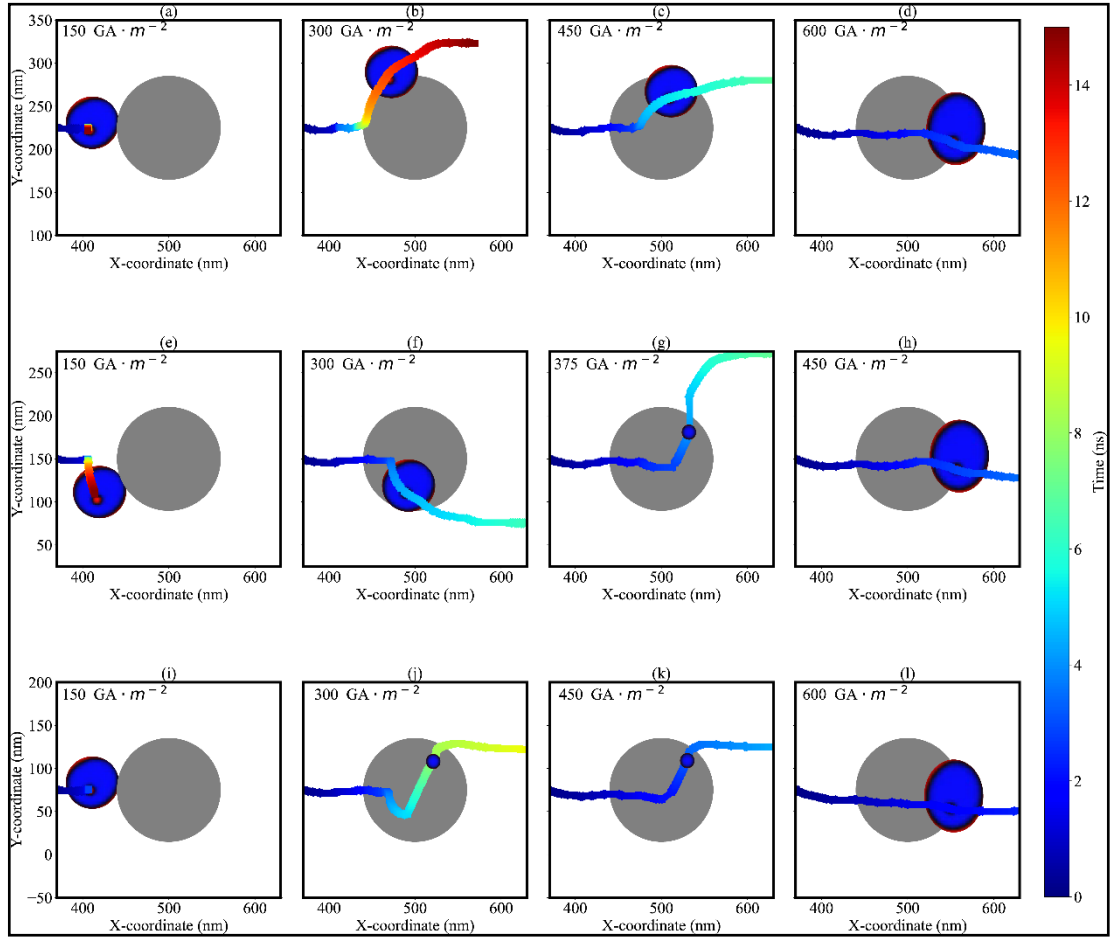


Figure 4.9: Skyrmionium/skyrmion trajectories for varying current densities on three different racetracks: (a-d) depict paths on a 450 nm wide racetrack, (e-h) illustrate paths on a 300 nm wide racetrack and (i-l) illustrate paths on a 150 nm wide racetrack. The colormap represents the time progression of the skyrmionium along each path, with the colorbar indicating the corresponding time in nanoseconds. Gray circles in the plots represents defect.

Finally, we employed a model with a 150 nm racetrack width. On this racetrack when the skyrmionium is driven through the defect we observed that three different outcomes are possible depending on the applied current density value. For the current density values between $J = 150 \text{ GA} \cdot \text{m}^{-2}$ and $J = 300 \text{ GA} \cdot \text{m}^{-2}$, the skyrmionium moves towards the defect on a straight path along the applied current (x-axis). When the skyrmionium reaches the defect boundary, it contacts the defect at the latter's boundary and becomes pinned at that position while keeping its form intact. The SOT exerted on the skyrmionium because of the applied current fails to overcome the repulsive force exerted on the skyrmionium by the defect's boundary, and the skyrmionium stops at the boundary while its shape is conserved, unlike the two previous models where the racetrack widths were larger (Fig. 4.8b). Pinning of skyrmionium was facilitated by the increased repulsion experienced by the skyrmionium from the edges of the narrower racetrack. This increased repulsion from the edges prevented the skyrmionium from sliding on the outer wall of the racetrack. The second possible outcome occurs for current density values between $J = 300 \text{ GA} \cdot \text{m}^{-2}$ and $J = 600 \text{ GA} \cdot \text{m}^{-2}$ in which case the SOT effect is strong enough to overcome the repelling force of the defect, and as a result, the skyrmionium is driven into the defect. Once completely inside the defect, the skyrmionium is not immediately released towards the centre of the defect for the applied current values given above, but it starts to slide along the defect's inner boundary [22]. During this sliding motion, as the skyrmionium moves closer to the edge of the racetrack, repulsion from the edges becomes stronger. Due to this repulsion, the skyrmionium gets depinned from the wall. Once it gets depinned, the skyrmionium undergoes a transformation within the defect, resulting in the formation of a skyrmion. After the transformation, the newly formed skyrmion starts moving at an angle of 60 degrees due to the SkHE and is released back into the racetrack by passing through the defect's upper boundary where it eventually reaches the upper edge of the racetrack. After reaching the upper edge of the racetrack, the skyrmion moves along a horizontal path towards the right end of the racetrack. As the current density increases from 300 to $450 \text{ GA} \cdot \text{m}^{-2}$, the sliding distance along the defect's inner boundary reduces and the skyrmionium is released from the inner boundary further into the defect faster compared to lower current density values. Once released from the inner boundary, the skyrmionium completes its transformation into a skyrmion and heads toward the upper edge of the defect. For current values higher than $J = 600 \text{ GA} \cdot \text{m}^{-2}$, the third possibility takes place and the skyrmionium passes

through the defect boundary and enters the defect without being affected much as the sliding motion ceases completely for $J = 600 \text{ GA} \cdot \text{m}^{-2}$. The skyrmionium then continues along its original path with minimal deviation. We found out that using a racetrack with a 150 nm width results in a more energy-efficient model. Even though the current density values are comparable between the models, the applied current is lowest on the 150 nm racetrack.

The motion of skyrmionium can be described by using Thiele's equation [37,57]:

$$-4\pi N_{sk} b e_z \times v - \alpha D b \cdot v - B I j = \nabla U(r) \quad (4.1)$$

Where N_{sk} is the skyrmion winding number, D is the dissipative tensor given by $D_{ij} = \int \partial_i m(r) \cdot \partial_j m(r) d^2 r$ where $D_{xx} = D_{yy} = D = \pi^2 R_{sk}/\Delta$. Here R_{sk} is the skyrmion radius and Δ is the domain wall width given by $\Delta = \sqrt{(A/K_{eff})}$. The torque tensor I is given by $I_{ij} = \int [\partial_i m(r) \times \partial_j m(r)] d^2 r$. This tensor describes the interaction between the injected spin s and the magnetic texture. The constants are $B = \left(\frac{\hbar}{2e}\right) \Theta_{sh}$ where Θ_{sh} is the spin hall angle and $b = (M_s/d_z) \gamma_e$ where M_s is the saturation magnetization, d_z is the thickness of the ferromagnetic layer and γ_e is the gyromagnetic ratio. For a skyrmionium, $N_{sk} = 0$ and the equation (3) becomes:

$$-\underline{D} \alpha b \dot{r} - B j \underline{I} s = \nabla U(r) \quad (4.2)$$

$$\dot{r} = -\frac{1}{D b} \nabla U(r) - \frac{B}{b} \frac{I_{xy}}{D} \frac{1}{\alpha} j \quad (4.3)$$

Where $U(r)$ is the potential created by the defect which can be assumed to be of the following form[15,58]:

$$U = C_0 e^{-\left(\frac{r_{i0}}{R_0}\right)^2} \quad (4.4)$$

Here C_0 is the pinning strength coefficient, R_0 is the radius of the defect, and r_{i0} is the distance between the skyrmionium and the defect. Using the potential given in 6 we can rewrite equation 5:

$$\dot{r} = 2 \frac{1}{Db} \frac{\vec{r}_{i0}}{R_0^2} U(r) - \frac{B}{b} \frac{I_{xy}}{D} \frac{1}{\alpha} j \quad (4.5)$$

Equation 4.5 implies that the motion of the skyrmionium depends on the potential created by the defect, the thickness of the ferromagnetic layer, the spin hall angle of the heavy metal layer, and the current density applied. In the simulations reported in this paper, the material parameters and the size of the defect were fixed, and only the applied current density varied in each simulation.

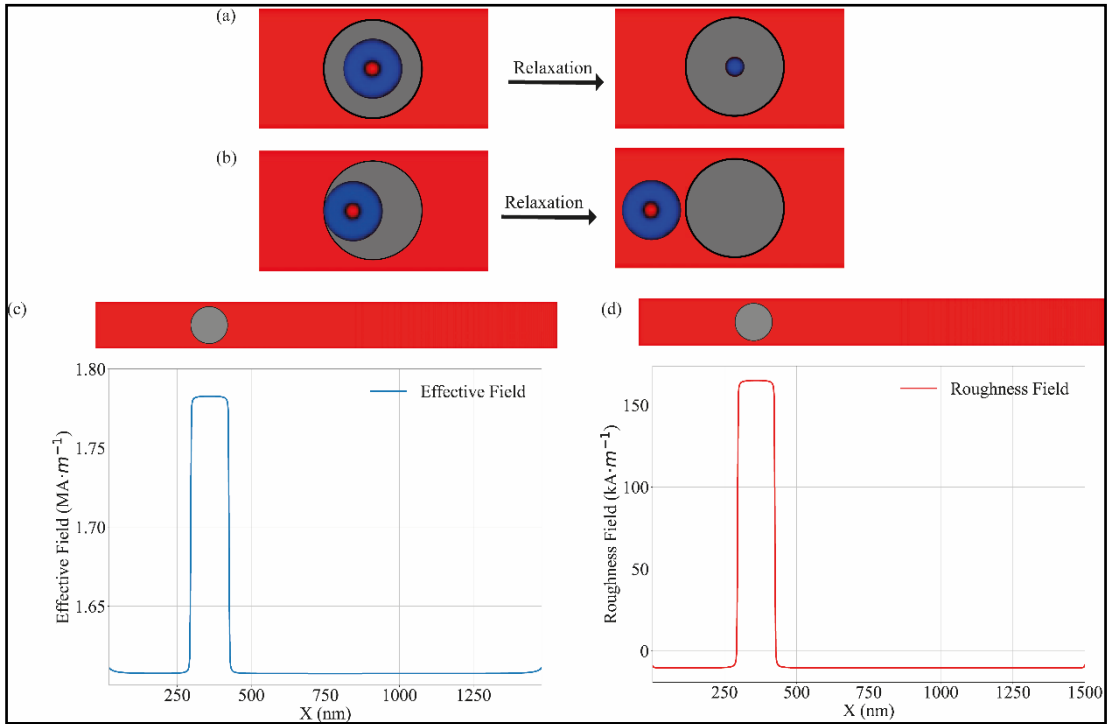


Figure 4.10: Relaxation process of a skyrmionium (a) at the center and (b) at the edge of the defect. Change in (c) effective field and (d) roughness field along the x axis of the racetrack. Due to the change in effective field skyrmionium is not stable inside the defect.

To investigate the conversion process of a skyrmionium to a skyrmion, we conducted two simulations: one with the skyrmionium initially placed at the centre of the defect and the other with the skyrmionium placed off-centre, towards the edge of the defect. After fixing the initial geometries, we conducted a relaxation of the system without any external forces, and the results are presented in Figure 4.10. For the first case where the skyrmionium was placed at the centre, we observed that the skyrmionium remained stationary during the relaxation process and eventually, the

skyrmionium transformed into a skyrmion. The circular symmetry of the defect and the skyrmionium resulted in a cancellation of the repulsive forces exerted by the walls of the defect, thus allowing the skyrmionium/skyrmion to remain at the centre before and after the transformation. The presence of the defect changes the roughness field in the racetrack, resulting in a higher effective field inside the defect as compared to outside. This change in the effective field destabilizes the skyrmionium by reducing its size, leading to its collapse into a skyrmion. Figure 4.10a and 4.10b illustrate this change in the effective field. The spin orbit torque effects dominate the skyrmionium motion for $J = 566 \text{ GA} \cdot \text{m}^{-2}$ or higher. As a result, the skyrmionium passes through the defect without significant modification in its topology.

The second case involved placing the skyrmionium at the edge of the defect and allowing it to relax without external forces. In this scenario, the repulsive force exerted on the skyrmionium by the defect boundary causes the skyrmionium to move outside the defect. As there is no force to counteract this motion, it continues until the force from the defect boundary is no longer sufficient to influence the skyrmionium's movement.

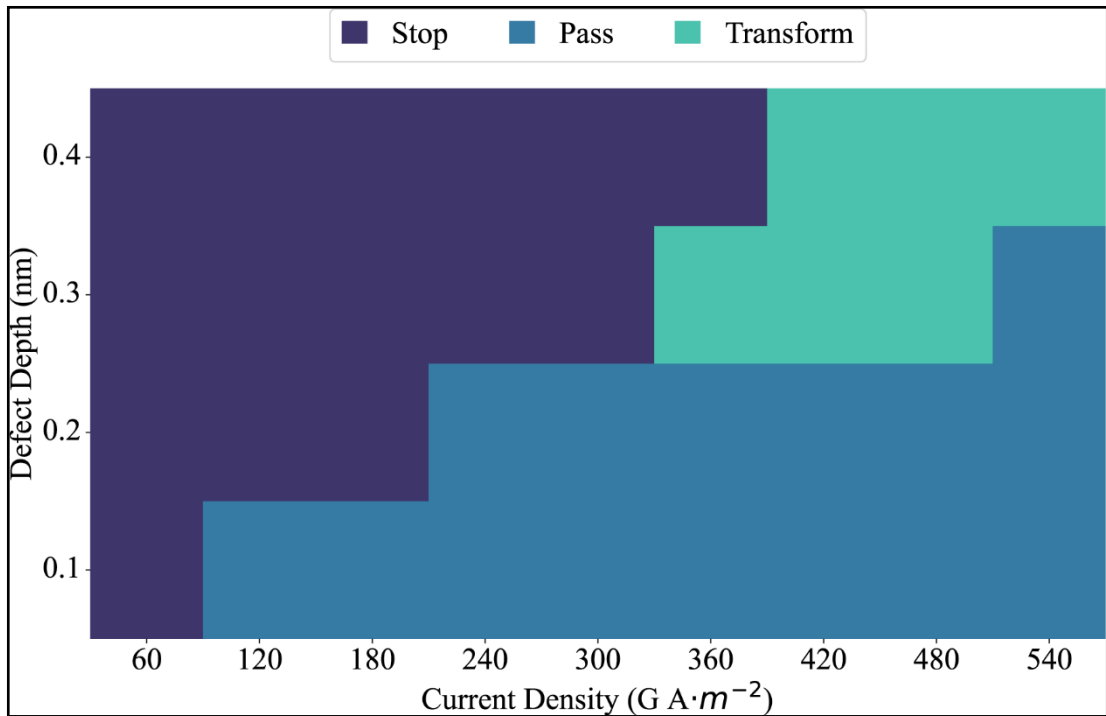


Figure 4.11: Effect of the defect depth on the outputs for different applied current values. As the defect depth increases higher current values are required due to the increase in repulsive potential of the defect.

In our quest to understand the complex dynamics of skyrmioniums, we conducted a series of simulations to investigate the impact of varying defect depths on the skyrmionium's motion and transformation. The results of these simulations, which are illustrated in Figure 4.11, provide a comprehensive view of how defect depth influences the behaviour of skyrmioniums.

Our findings reveal that even a minor disturbance of 0.1 nm in the z-axis is sufficient to impede the skyrmionium's motion at low current densities. This observation underscores the sensitivity of skyrmioniums to changes in their environment, even when these changes are relatively small.

As we increased the defect depth from 0.1 nm to 0.2 nm, we observed a corresponding increase in the critical current density required for motion. However, despite this increase in current density, no transformation of the skyrmionium took place. This suggests that while defect depth and current density are important factors in the motion of skyrmioniums, they do not necessarily trigger a transformation.

When we further increased the defect depth to 0.3 nm, a transformation to a skyrmion was observed within the range of $J = 2 \text{ GA} \cdot \text{m}^{-2}$ to $J = 5.4 \text{ GA} \cdot \text{m}^{-2}$. At this depth, the critical current value that prevents any transformation of the skyrmionium is $J = 5.6 \text{ GA} \cdot \text{m}^{-2}$. This finding indicates that there is a threshold defect depth at which a skyrmionium will transform into a skyrmion, and that this threshold can be influenced by the current density.

As we continued to increase the defect depth to 0.4 nm, the skyrmionium could no longer pass through the defect. This is attributed to an amplification in the change in the effective field within the defect and the repulsive forces exerted by its walls as the defect depth increases. Consequently, a higher current density is needed for a skyrmionium to traverse this defect without transforming. However, at greater depths, increasing the current density will only lead to deformation of the skyrmionium. This suggests that there is an upper limit to the defect depth that a skyrmionium can navigate without undergoing a transformation or deformation.

Taking all these factors into consideration, it appears that in our model, the upper limit for the transition process is a defect depth of 0.4 nm. Consequently, beyond a specific depth, a skyrmionium invariably transmutes into a skyrmion inside the defect. Furthermore, as depth rises, it necessitates a greater current density for the skyrmionium to surmount the defect wall's repulsion. Notably, based on preceding studies on skyrmioniums, their form begins to deform as current density rises. This

implies that any further augmentation in current density beyond $600 \text{ GA} \cdot \text{m}^{-2}$ threatens the stability of the skyrmionium. As such, it can be inferred that the current density does reach a saturation point for a particular depth, ensuring the stability of the skyrmionium. This understanding of the interplay between defect depth, current density, and skyrmionium behaviour is crucial for the manipulation and control of skyrmioniums in spintronic devices.

After thoroughly examining the influence of defect depth on the motion and transformation of skyrmioniums, we now shift our focus to another critical aspect of the defect structure - its shape. The shape of a defect, much like its depth, can significantly impact the behaviour of a skyrmionium, influencing its trajectory and potential for transformation. In this section, we delve deeper into the effects of varying defect shapes on the motion and transformation of skyrmioniums. We explore how different geometric configurations can alter the interaction dynamics between the skyrmionium and the defect, leading to a variety of outcomes.

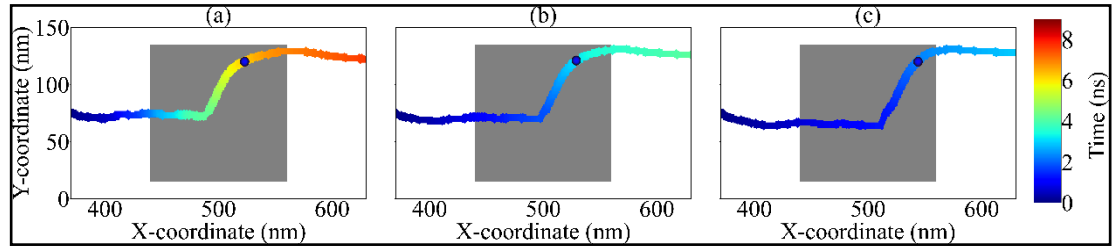


Figure 4.12 Skyrmionium/skyrmion paths for varying current densities on a square-shaped defect: (a) 150 GA/m^2 , (b) 300 GA/m^2 , and (c) 600 GA/m^2 . The colormap represents the time progression of the skyrmionium along each path, with the colour bar indicating the corresponding time in nanoseconds. Gray squares in the plots represent the square-shaped defect.

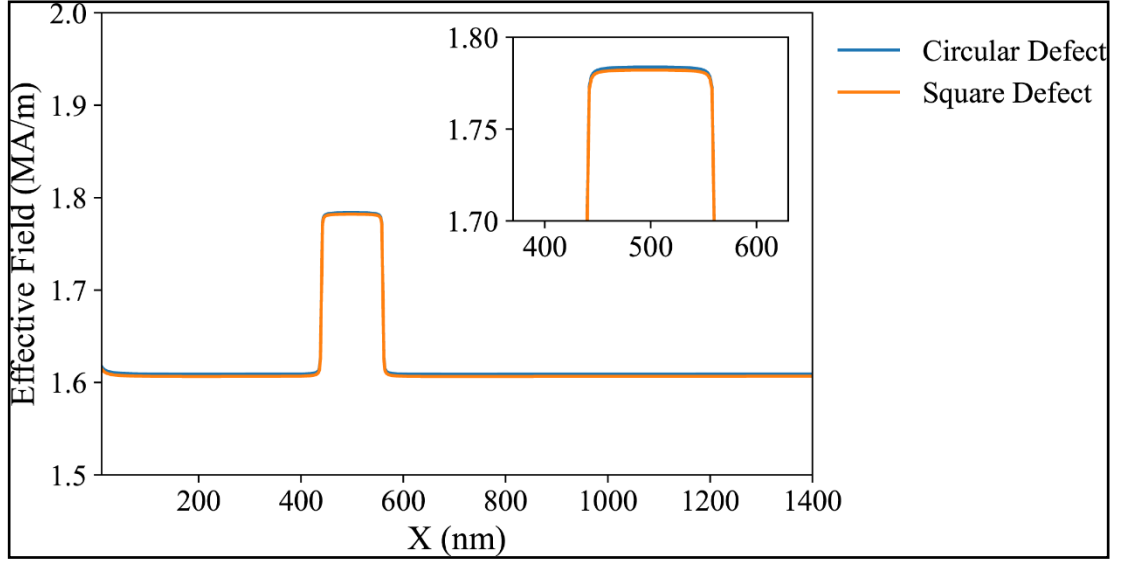


Figure 4.13: Change in the effective field inside the circular and square-shaped defects

The results obtained from these simulations unveiled differences compared to the outcomes observed for the circular defects. Upon reaching the crater boundary, due to the change in orientation of the defect wall, the force exerted on the skyrmionium by the wall is different from that of the circular defect. These results are consistent with the literature [22]. The change in the orientation of the wall has an impact on the current density values, which in turn influences the observed outcomes.

The change in the wall's orientation also impacts the current density values, which in turn influence the observed outcomes. As we further increase the current density, the skyrmionium is forced into the square defect. Once inside the defect, the skyrmionium undergoes a transformation, resulting in the formation of a skyrmion. This transformation occurs over a larger range compared to the circular defect, indicating that the shape of the defect plays a significant role in the transformation process.

Interestingly, we found that the circular symmetry of the defect leads to greater stability for the skyrmionium compared to the four-fold symmetry of the square defect. In the square configuration, the force applied on the skyrmion exhibits a higher gradient due to the change in symmetry, causing the skyrmionium to be less stable.

In conclusion, our additional investigation into the impact of square-shaped defects on skyrmionium behaviour has provided valuable insights into the role of defect symmetry in the system. While the circular and square-shaped defects exhibit distinct differences in the force applied on the skyrmionium and its stability, it is

important to further explore the influence of various defect geometries and their potential applications. This exploration could pave the way for new strategies in the manipulation and control of skyrmioniums, opening new avenues for research and potential applications in spintronic devices.

5. DISCUSSION

In this thesis, we conducted extensive simulations to investigate the nucleation of skyrmioniums and their interaction with engineered defects placed on a racetrack. Nucleation is achieved by injecting two pulses of spin polarized current in the opposite direction to a circular contact. After the nucleation, the skyrmionium is placed on a racetrack. An in-plane current is then applied to move the skyrmionium along the +x axis. A thickness perturbation is placed along the path of the skyrmionium with varying depths and shapes to investigate the interaction of the defect and the skyrmionium.

Our results demonstrate that even a small disturbance of 0.1 nm in the z-axis is sufficient to hinder the skyrmionium's motion at low current densities. As the defect depth is increased from 0.1 nm to 0.2 nm, the critical current density required for motion also rises, but no transformation takes place. For a depth of 0.3 nm, a transformation to a skyrmion is observed within the range of $J = 2 \text{ GA} \cdot \text{m}^{-2}$ to $J = 5.4 \text{ GA} \cdot \text{m}^{-2}$. At this depth, the critical current value that prevents any transformation of the skyrmionium is $J = 5.6 \text{ GA} \cdot \text{m}^{-2}$. This is due to an increase in the effective field within the defect and the repulsive forces exerted by its walls. Consequently, a higher current density is needed for a skyrmionium to traverse this defect without transforming. However, at greater depths, increasing the current density will only lead to deformation of the skyrmionium. Taking all these factors into consideration, it appears that in our model, the upper limit for the transition process is a defect depth of 0.4 nm.

During our research, we have identified several potential strategies for reducing the current density required to drive skyrmionium motion. These strategies are rooted in the Thiele equation, which describes the current density as a function of several factors, including the dissipative tensor $D_{xx} = D_{yy} = D = \pi^2 R_{sk}/\Delta$ (related to skyrmionium size), where $\Delta = \sqrt{(A/K_{eff})}$ is the domain wall width; constant B and b are defined as $B = \left(\frac{\hbar}{2e}\right) \Theta_{sh}$ where Θ_{sh} is the spin hall angle and $b = (M_s/d_z)\gamma_e$, respectively; M_s is the saturation magnetization; d_z is the thickness of the ferromagnetic layer and γ_e is the gyro-magnetic ratio. By modifying the properties of the ferromagnetic (FM) layer, adjusting the FM layer thickness, altering the crater size

and depth, or employing a different heavy metal (HM) layer with a distinct spin Hall angle, it may be possible to achieve a reduction in the required current density.

Looking ahead, it could be valuable to investigate the effects of using different materials for the magnetic layer, such as TmIG/Pt, or employing entirely different stacks like $\text{Bi}_2\text{Se}_3/\text{BaFe}_{12}\text{O}_{19}$ [59]. Such investigations could provide insights into the development of more efficient and adaptable skyrmionic devices and enhance our understanding of the interplay between material properties and device functionality. We are currently exploring these and other possibilities in our ongoing research.

In our simulations, we assumed an idealized scenario involving monolayer-sized defects without considering the effects of surface roughness. While this provides insights into skyrmionium-defect interactions under perfect conditions, it is crucial to recognize the practical challenges in fabricating samples with this type of a defect which has a size comparable to the roughness scale in real materials. Two-dimensional (2D) materials emerge as a potential solution to this problem.

Nanosheets of 2D materials can be synthesized from their bulk crystals through a process known as exfoliation, which produces large nanosheets that can be several hundreds of micrometres in lateral dimensions but only a few atomic layers thick, in some cases even monolayer [60]. This enables a high degree of flatness, effectively mitigating issues related to surface roughness.

One of the intriguing aspects of 2D materials is their layer-dependent magnetic properties. For instance, chromium triiodide (CrI_3) and iron germanium telluride (Fe_3GeTe_2) have been garnering attention for their unique magnetic properties. CrI_3 transitions from an antiferromagnetic state in the bulk form to ferromagnetic when reduced to a monolayer, which is a striking manifestation of how 2D confinement can dramatically alter material properties. Similarly, Fe_3GeTe_2 exhibits a strong in-plane magnetic anisotropy with tuneable ferromagnetism based on the number of layers [61].

This layer-dependent tunability of magnetic properties in 2D materials can be harnessed for engineering structures explained in this thesis. With the ability to control magnetic states and anisotropy by manipulating the thickness, 2D materials like CrI_3 and Fe_3GeTe_2 offer a flexible platform for designing skyrmions with desired properties. Additionally, the intrinsic flatness of 2D materials could alleviate the challenges posed by surface roughness, paving the way for more reliable and precise skyrmion manipulation.

Apart from CrI_3 and Fe_3GeTe_2 , there are other 2D magnetic materials such as VSe_2 and MnBi_2Te_4 , which have also been reported to exhibit tuneable magnetic properties [62]. These materials could be explored further for suitability in skyrmionic applications.

It is also worth mentioning that integrating 2D materials into heterostructures by stacking different 2D materials can further expand the design space for novel magnetic devices, allowing for the creation of complex magnetic profiles and coupling phenomena [63]. Combining 2D materials with contrasting properties in a layered configuration, one can engineer new phases and phenomena that are not present in the individual materials. For example, stacking a ferromagnetic 2D material with a topological insulator can result in a hybrid system with emergent topological magnetism [64].

Furthermore, 2D materials with their reduced dimensionality can potentially enable more energy-efficient skyrmion manipulation, as the ultrathin nature of these materials might reduce the current densities required for skyrmion motion via spin-orbit torques. This can also contribute to the scaling down of skyrmionic devices, making them even more attractive for high-density data storage applications.

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BIOGRAPHY

Aykut Can Önel started Gebze Yüksek Teknoloji Enstitüsü Physics Department in 2006 and graduated in 2011. In January 2012, he started his Master's degree in the Graduate School of Natural and Applied Sciences Physics Department in the same University and completed his Master's degree in 2014. After completing his Master's Degree he started doing his PhD in the same year and same department. He also worked at Tübitak National Metrology Institute Quantum Metrology Lab. in 2020 and finished his work in 2023.

APPENDICES

Appendix A: Publications Within the Scope of Thesis Study

Önel A. C., Çimen M., Yarimbiyik A. E., Arikan M., Rameev B., (2023), “Interaction of a Magnetic Skyrmionium With an Engineered Defect.”, Journal of Superconductivity and Novel Magnetism.