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Research articles

Theory of current-induced skyrmion dynamics close to a boundary

J.C. Martinez[a,*], W.S. Lew[b], W.L. Gan[b], M.B.A. Jalil[a]

[a] *Computational Nanoelectronics and Nano-device Laboratory, National University of Singapore, 4 Engineering Drive 3, Singapore 117576, Singapore*
[b] *School of Physical and Mathematical Sciences, 21 Nanyang Link, Nanyang Technological University, Singapore 637371, Singapore*

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ABSTRACT

Skyrmions are the prime candidate as the information carrier of tomorrow's data storage devices. But they face the risk of annihilation on encountering a boundary. We show how skyrmions can avoid this undesired outcome through management of their anisotropy energies. Specifically we derive an edge potential and a contact interaction term which only operate close to the edge. We verify the accuracy of these two terms by modelling a realistic skyrmion system and comparing it with micromagnetic simulations. We not only observe and explain the speeding up of skyrmions near the edge (which had been expected) but also observe and explain a peculiar asymmetry in the motion (where it speeds up more on one edge compared to the other). We devise a means to stabilize a skyrmion against Magnus force (without the need for a transverse current) by modifying the damping parameters. Finally, we note a link between these damping parameters and the anisotropy energy. Our results will be of value in the design of skyrmion-based devices and would give fresh impetus to the study of magnetic anisotropy.

Significance: Skyrmions are the prime candidate as information carrier of tomorrow's ever ubiquitous data storage devices. But they face the risk of annihilation on encountering a boundary. We propose a model for the skyrmion-edge dynamics by deriving an edge potential and a contact interaction, which are incorporated into the standard Thiele equation for the current-induced motion of skyrmions. We compare this model with micromagnetic simulations which leads us to observe and explain the speeding up of skyrmions near the edge. We also observe and explain a peculiar asymmetry in the motion (where skyrmions speed up more on one edge compared to the other) and discover the important role played by the damping constants of the Thiele equation. We devised a means to stabilize a skyrmion against Magnus force (without the need for a transverse current) by modifying the damping parameters. A connection with the anisotropy energy is noted.

1. Introduction

Today's appetite for data and memory-device applications is being largely quenched by spintronics-research findings from over the past three decades, with current-induced phenomena in ferromagnets playing a leading role. Within this arena, attention has recently shifted onto the role of magnetic skyrmions in chiral helimagnets as information carriers [1]. Real devices are usually modelled upon planar geometries without boundaries but it is becoming increasing clear that boundary effects are not mere perturbations or harmless artefacts [2,3]. In fact the fate of skyrmions encountering a boundary is annihilation. We show in this paper that skyrmions can move even faster along a finite channel [4,5] and discuss how to optimize this circumstance. Thus what is new in this work is the management of the edge dynamics *in conjunction with* anisotropy engineering for the efficient control of skyrmion transport close to the track edge. These findings will be useful in the design and utilization of skyrmion-based devices and would also stimulate further studies in magnetic anisotropy.

Magnetic skyrmions are stable nano-sized vortex-swirls in non-centrosymmetric crystals harbouring great promise as information carriers and can be induced to motion under extremely low spin current densities [6–8]. For reviews see Refs. [9,10]. They have been created recently at room temperature and a demonstration of the controlled writing and deleting of skyrmions by spin-current injection has been lately achieved [11–13]. Skyrmions are produced in chiral magnets in the presence of the Dzyaloshinkii-Moriya interaction (DMI) which is also responsible in part for their remarkable stability [14]. In the past two years, skyrmions stabilized without or only partially by the DMI have been discussed and proposed as information carriers in the context of frustrated magnets in nanostrips [12,14–17]. We will not focus on these systems here.

Many applications of skyrmions as information carriers will require them to move on a track. An acute problem already noted above is their tendency to migrate toward an edge or boundary and annihilate there

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[*] Corresponding author.
E-mail address: avecrux5@gmail.com (J.C. Martinez).

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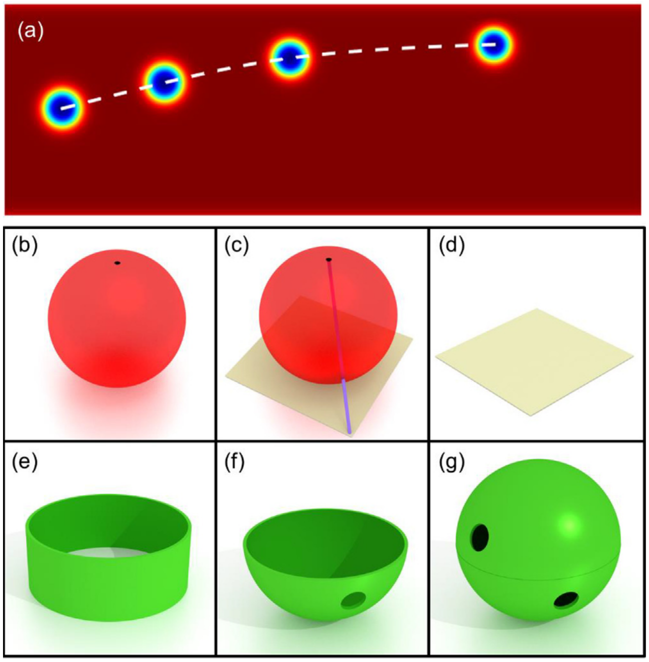

Fig. 1. Skyrmion trajectory and topology of an infinite plane and a finite channel: (a) Skyrmion trajectory on a finite track under a forward current to the right. The trajectory is generated from micromagnetic simulations which records positions at 0, 2, 4, 6 ns (see MethodsX, Section D). Note a drift upward caused by the Magnus force which ultimately pushes the skyrmion to the upper edge where it loses its topological protection and annihilates. (b) A plane is topological equivalent to a sphere with its North pole removed as shown by the homeomorphism between these surfaces via a stereographic projection from the North Pole (c) and (d). Similarly a finite track can be rolled into a cylinder (e) which in turn is homeomorphic to a hemisphere with a hole (f) or to a sphere with two points deleted (g). Thus a finite channel is topological distinct from a plane.

since they lose their topological protection at the edge. This is because of the Magnus force whereby current-induced motion is accompanied by a strong sideways force [19,20]. See Fig. 1(a). Skyrmions might avoid wandering by an edge if thermally induced magnons are able to cancel out the Magnus displacement [21]. However this scheme appears more complicated than the original system. Another way is for two perpendicularly magnetized ferromagnetic sublayers to couple antiferromagnetically with a heavy-metal layer beneath [22]. Skyrmion pairs of opposite vorticity are simultaneously created in the top and bottom layers and the pairs are capable of suppressing the Magnus displacement. Still another possibility is the use of a magnetic potential at the edges to confine skyrmions [23]. Despite their manifest merits, these all require *additional* elements integrated into the existing system.

In this paper we leave the track as is, but take advantage of the properties of the track edge, suitably re-engineering its anisotropy energies, so that annihilation is avoided *and* the skyrmions close to the edge are boosted forward faster those in the vicinity of the centre. We will also see that the spin-orbit interaction's role in the anisotropy energy is necessary in attaining these goals. A finite track is not infinite and a skyrmion is on the track only while it is traversing it and the skyrmion-migration problem is gone once the track is cleared.

Because our focus here is on skyrmion transport on finite tracks, it is important to establish early on the fundamental difference between finite and infinite tracks. Unlike the latter any finite track is not translationally invariant. Translation invariance is invoked to argue that skyrmions only experience the Magnus force, the dissipative force and whatever potential forces are present [18]. But this may be lost near an edge where left and right no longer pair. For any point on an infinite plane, a force from its left will be balanced by another from the right. Elements present in the plane may disappear in the finite channel and vice versa. Fig. 1(b–d) show how the plane is homeomorphic to a sphere with *one* point deleted, whereas a finite track is homeomorphic to a sphere with *two* points deleted (Fig. 1e–g). Moreover, we plot in Fig. 2 the configurations of the magnetization, the DMI and exchange fields on a track obtained from micromagnetic calculations; we see that the centre, whose environment resembles a plane, differs indeed from the environment of a point near an edge/boundary: the thinner the channel the greater that difference. Clearly the centre and edge environments are not merely different but fundamentally inequivalent: the axis-symmetry at the centre gives way to quasi-one-dimensional dynamics in the direction perpendicular to the edge.

In Section 2 we propose an analytical model for the skyrmion-edge dynamics by deriving expressions for the edge potential and contact interaction. These are two special features that figure when skyrmions are close to an edge. These are then incorporated into the standard Thiele equation for the current-induced motion of skyrmions in a finite channel. Armed with these tools we compare in Section 3.1 the model with micromagnetic simulations which leads us to observe and explain the speeding up of skyrmions near the edge. We also observe and explain a peculiar asymmetry in the motion (where skyrmions speed up more on one edge compared to the other) and discover the important role played by the damping constants of the Thiele equation in skyrmion transport. We devised in Section 3.2 a means to stabilize a skyrmion against Magnus force (without the need for a transverse current) by modifying the damping parameters. Finally in Section 3.3 we suggest future prospects and end with our conclusions.

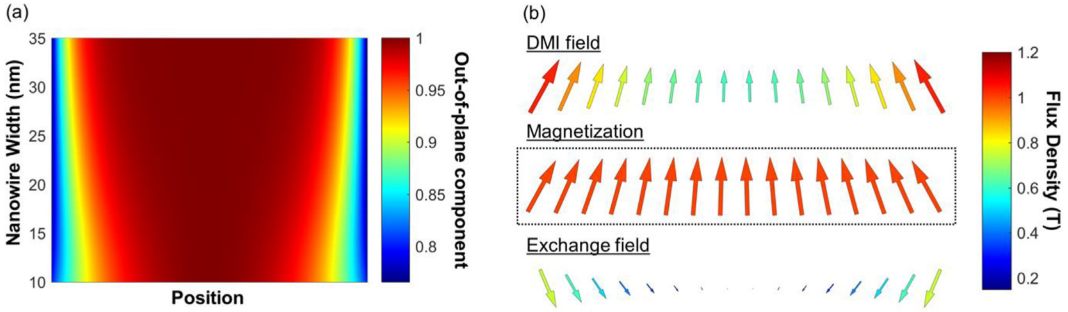

Fig. 2. Plots of the magnetization, exchange and DMI fields for a channel: (a) Variation of the out-of-plane magnetization across a finite width channel in a relaxed state versus position X in the channel, obtained from micromagnetic simulation (with periodic boundary conditions along X). The channel width (horizontal direction) is scaled to unity for any width. Colour gives the value of the reduced magnetization while the vertical axis gives the channel width. As noted in the MethodsX Section D, simulations should be for channel widths greater than 10 nm to be reliable. (b) Variation of the DMI (top) and exchange (bottom) fields across a 15 nm wide channel. The presence of growing fields close to the edge induces chiral twists. At the centre the magnetization is axisymmetric while at the edge it can be expected to display one-dimensional features in the direction perpendicular to the edge. These plots support the same conclusion in Fig. 1 that the plane and channel have fundamentally distinct physical environments.