Skyrmion formation in magnetic thin films and heterostructures

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Magnetic skyrmions are small magnetic domains that are topologically non-trivial as shown schematically in Fig. 1. They are characterized by a twist of the magnetization that forms a continuous winding of the magnetization across the domain. The topology is described by a quantized and conserved winding number. The term skyrmion arises from the original work of Skyrme some fifty years ago that described baryons as topological defects of continuous fields. These defects could be considered "protected" because they were characterized by a topological integer that cannot be changed through any continuous deformation of the field. Since then "skyrmion" states have been found in condensed matter systems such as liquid crystals, quantum Hall systems, ferroelectrics, and magnetic materials. The interest in magnetic skyrmions is driven by novel physics and potential applications. The spin texture topology "protects" skyrmions from scattering by structural defects, allowing them to be moved with ~10^5 times lower current density than a conventional magnetic domain. These features make magnetic skyrmions appealing for low power memory and information processing applications based on spin torque transfer and the topological spin Hall effect. We have ongoing research into the discovery of new magnetic materials hosting skyrmions, the observation of novel properties of skyrmions and the integration into skyrmion-based devices [1-5].

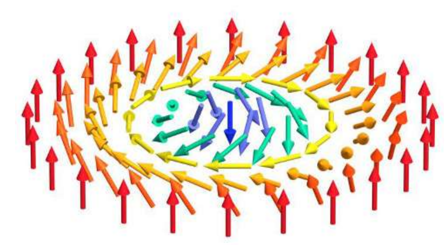

Figure 1: Schematic spin structure of a magnetic skyrmion showing a continuous winding of the magnetization.

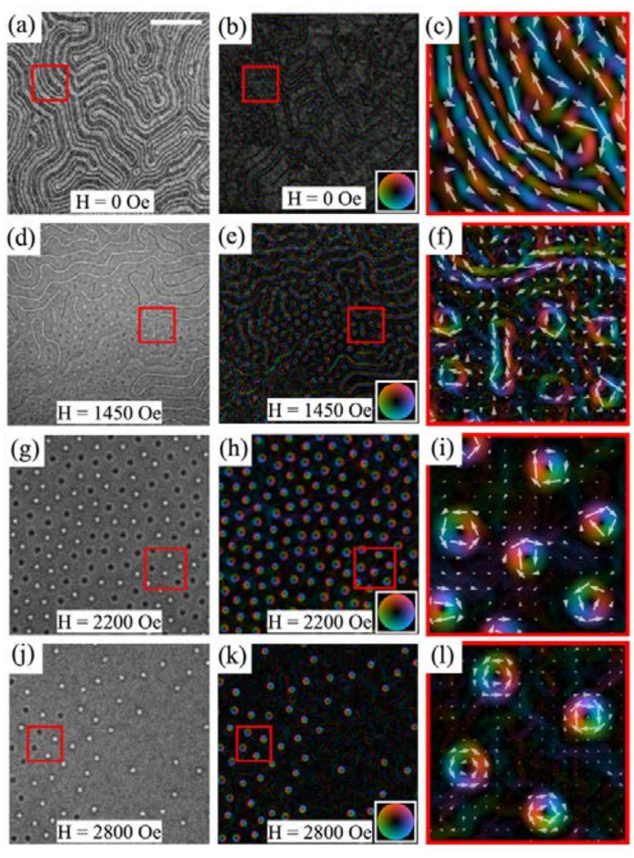

Figure 2: Real space imaging of the field-dependent magnetic domain morphology of Fe/Gd multilayers. Under-focused Lorentz TEM images (first column) measured at room temperature and their corresponding magnetic induction color maps (second and third columns) are detailed. Four different magnetic states are observed as a function of field, including: disordered stripe domains. The scale bar in (a) corresponds to 1μm.

There are increasing number of magnetic materials where skyrmions have been observed from bulk magnets to thin films and have been shown to be stable under several physical mechanisms. The most heavily studied mechanism to stabilize skyrmions is the Dzyaloshinskii-Moriya interaction arising in non-centrosymmetric magnetic materials or thin films. However, topologically similar spin structures can be stabilized by the competition of long-range dipolar energy in a thin film geometry and domain wall energy, a mechanism by which magnetic stripes and bubbles form. Commonly a chiral magnetic bubble is termed a dipole stabilized skyrmion given the resemblance to a Bloch-type Dzyaloshinskii-Moriya interaction skyrmion shown in Fig. 1 where the domain wall is a

Bloch wall. These chiral bubbles or dipole-stabilized skyrmions present a test-bed to explore how the balance of ferromagnetic exchange, anisotropy and dipolar energy results in domains that are topologically non-trivial and to explore their properties.

Shown in Fig. 2 are imaging results for an Fe/Gd multilayers film where we have used the unique features of the ferrimagnetic Fe/Gd system to tune the magnetization, anisotropy, and exchange [1-3]. This has allowed us to stabilize isolated or closed-packed lattices of bound skyrmion molecules [1] or dipole skyrmions [2] under the application of a magnetic field, which are sub-100-nm is size [2]. Unlike in Dzyaloshinskii-Moriya interaction materials, the dipole skyrmion phase consists of an equal population of chiral domains with two possible helicities. Since the Bloch-line continuously wraps around the magnetic texture, we define it as a dipole skyrmion that possesses a winding number S = 1. If the Bloch-line wraps itself around in a clockwise direction it has helicity $\gamma = -\pi/2$; conversely, a Bloch-line wall that wraps counter-clockwise has helicity $\gamma = +\pi/2$. Skyrmion molecules (or bi-skyrmions) are when two skyrmions of opposite chirality are bound together [1]. To probe the physics of these skyrmions we have probed them with neutron reflectivity, resonant soft x-ray scattering, resonant soft x-ray imaging, Lorentz TEM (Fig. 2), ferromagnetic resonance, magneto-transport and modeling [1-4].

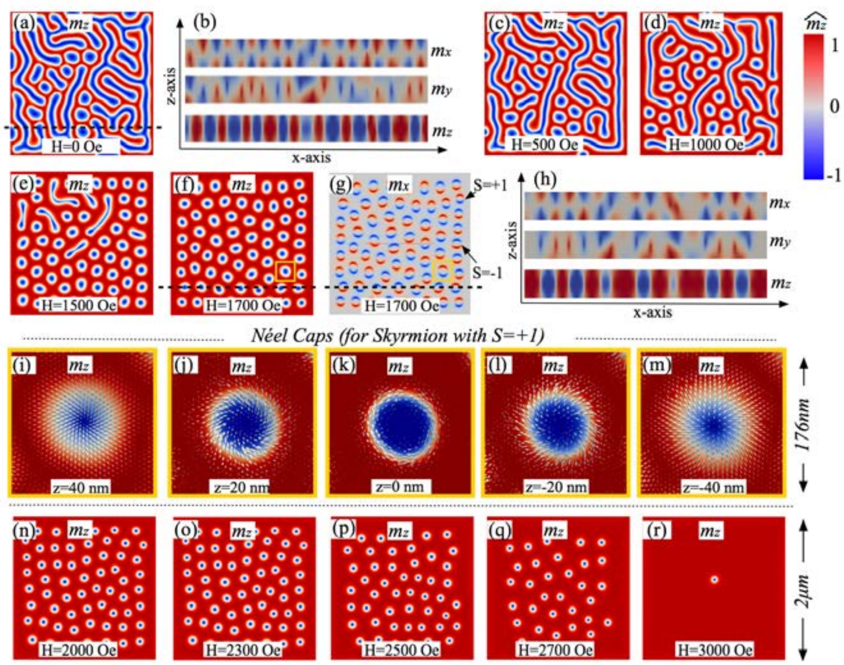

Figure 3: Micromagnetic modeling of domain morphology. (a-r). These images primarily depict the top side view of the magnetization along the z-axis (m_z) at the top surface of the slab (z=40nm). The magnetization (m_z) is represented by regions in red ($+m_z$) and blue ($-m_z$); whereas the in-plane magnetization (m_x, m_y) is represented by white regions surrounding the blue features. **(b, h)** Illustrates the lateral magnetization components (m_x, m_y, m_z) across the film thickness for the disordered stripe domains in **(a)** and the skyrmion phase in **(f, g)** along the dashed line. Inspection along the lateral magnetization reveals a Bloch-like wall configuration with closure domains in both states. The chirality of the skyrmions is depicted in **(g)** along top side-view of m_x across the center of the slab. **(i-m)** Detail the magnetization distribution at different depths (z=40, 20, 0, -20, -40nm) for a skyrmion with chirality S = +1, $\gamma = -\pi/2$ that is enclosed in a box in **(f, g).** At each depth, the perpendicular magnetization is represented by blue ($-m_z$) and red ($+m_z$) regions and the in-plane magnetization distribution (m_x and m_y) is depicted by white arrows. The white arrows illustrate how the magnetization of the closure domains and Bloch-line arrange at different depths of the slab. **(n-r)** Detail the field evolution from an ordered skyrmions to disordered skyrmions

To understand the detailed three-dimensional magnetic structure of the skyrmion we compared our experimental results to micro-magnetic simulations performed using the FASTMag framework developed at UCSD. Examples are shown in Fig. 3 where we are able to reproduce many of the experimental features in Figs. 2 including both the transition from stripe to skyrmions phases with increasing applied magnetic field using the average properties of the sample. The modeling (Fig. 3) also shows a complex 3-D structure (that is not reflected in the 2-D images in Fig. 2 that are averaged over the thickness of the film) with relatively broad domains walls that have both Néel and Bloch character and closure domains that form towards the surfaces as shown in Fig. 3. We have further been able to probe the resonant properties in modeling and compare the results to ferromagnetic resonant measurements [3].

The Lorentz-TEM images (Fig. 2) and numerical simulations (Fig. 3) suggests the stabilization of these skyrmions is purely driven by competing dipolar and exchange energies and that no Dzyaloshinskii-Moriya interaction is present in these films. The Lorentz-TEM images show two helicity textures with an equal population distribution in the skyrmion phase. If some Dzyaloshinskii-Moriya interaction were present, then the system would likely favor the formation of a one chiral domain compared to the other, as well as one Néel cap orientation over the other which is not the case here. The fact that we numerically observe the stabilization of the same 2-helicity skyrmions in simulations with no Dzyaloshinskii-Moriya interaction supports this observation. Given the nature of these skyrmions we can observe skyrmion molecules and these films could potentially also be designed to host anti-skyrmions as recently theoretically predicted. Unlike bubble domains which typically observed in materials with perpendicular magnetic anisotropy, our chiral domains appear in a material parameter space where the anisotropy is relatively low and the formation of perpendicular domains results from a thickness driven domain morphology rearrangement.

We have shown that by tuning the magnetic properties and film thickness we can control the stabilization of skyrmion phases in temperature and applied magnetic fields. The simplicity of the magnetic material and the easily tunable properties makes it of interest for studying physics of skyrmions, as well as, for potential memory technologies. We are currently studying the magneto-transport properties and the potential for current-induced control of the skyrmion and skyrmion lattice. Furthermore, the universality of our numerical model presents a roadmap to design new classes of materials that can exhibit dipolar field driven skyrmions. This work was the focus of the Ph.D. thesis of Sergio Montoya [5] and was done in collaboration with S. A. Montoya, S. Couture, J. J. Chess, J. C. T Lee, N. Kent, D. Henze, M.-Y. Im, S.D. Kevan, P. Fischer, B. J. McMorran, V. Lomakin, S. Roy, and S. K. Sinha.

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