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Topological Magnetic States and their Properties

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Skyrmions are topologically non-trivial particle-like magnetic spin textures that exhibit novel physics and potential technological applications [1-3]. These spin textures are usually stabilized by Dzyaloshinskii-Moriya interaction (DMI) that arises in non-centrosymmetric bulk magnets or thin ferromagnetic film heterostructures with asymmetric transition metal interfaces that possess high-spin orbit coupling. Topologically equivalent magnetic spin textures can also be stabilized by the competition of dipole energy and domain wall energy, termed dipole skyrmions [4]. A skyrmion is characterized in terms of a topological number S, defined as: $S = \frac{1}{4\pi} \int M \cdot \left(\partial_x M \times \partial_y M\right) dxdy$. The topological nature of a skyrmion enables some of its unique properties, such as: current-driven motion with low current densities, topological Hall effect, skyrmion Hall effect, localized non-trivial spin wave dynamical modes resulting from microwave perturbations, among other characteristics.

This talk focuses on recent developments in stabilizing, manipulating and designing topologically non-trivial magnetic states in thin film heterostructures. Using a combination of real- and reciprocal-space measurements, such as Lorentz transmission electron microscopy, full-field transmission soft x-ray microscopy and resonant soft x-ray scattering, we demonstrate the formation of various topological magnetic spin structures such as achiral bubbles ($S = 0$), skyrmions ($S = 1$), bi-skyrmions ($S = 2$) [5] and anti-skyrmions ($S = -1$) which arrange in either closed-packed lattice or isolated magnetic phases. Emphasis is given to dipole skyrmions ($S = 1$) [4] and their properties.

First, we show that sub-100nm dipole skyrmions are achievable in magnetic specimens where the thin-film shape anisotropy $2\pi M_S^2$ exceeds the uniaxial anisotropy K_U. The ratio $Q = K_U / 2\pi M_S^2$, commonly referred as a material's Q-factor is < 1. A dipole skyrmion exhibits a complex spin structure that varies across the magnetic specimen thickness: along the center of the slab it exhibits a Bloch-like wall configuration that broadens and transitions to Néel-like walls towards the film surface which are often referred to as closure domains or Néel caps (Fig. 1). Unlike DMI skyrmions, a dipole skyrmion phase consists of an equal population of chiral cylindrical-like spin textures with two possible helicities such that, on average, the material is achiral.

Numerical simulations of the Landau-Lifshitz-Gilbert (LLG) equation, utilizing the FastMag solver, enables us to explore the magnetic energy parameter space to determine the different ratios of magnetization M_S, uniaxial anisotropy K_U and exchange interaction A that result in formation of dipole skyrmions. We show that proper combinations of (M_S, K_U, A) can result in dipole skyrmion phases for a slab of a given thickness, and we observe dipole skyrmion feature size can be correlated to the magnetic slab thickness. Experimentally, we demonstrate dipole skyrmions with features down to 20-nm are achievable utilizing highly tunable magnetic properties of amorphous Fe/Gd multilayer films.

We also demonstrate deterministic current-induced displacement of sub-100nm dipole skyrmions by spin-transfer effect [6]. Experiments are performed on amorphous Fe/Gd multilayers that are patterned into wires and exhibit stripe domains and dipole skyrmions at room temperature. The magnetic textures exhibit motion under current excitations with a current density ~10^8 A/m^2. We present current-induced dynamics for different magnetic phases, including disordered stripe domains, coexisting stripes and dipole skyrmions and a closed packed dipole skyrmion lattice.

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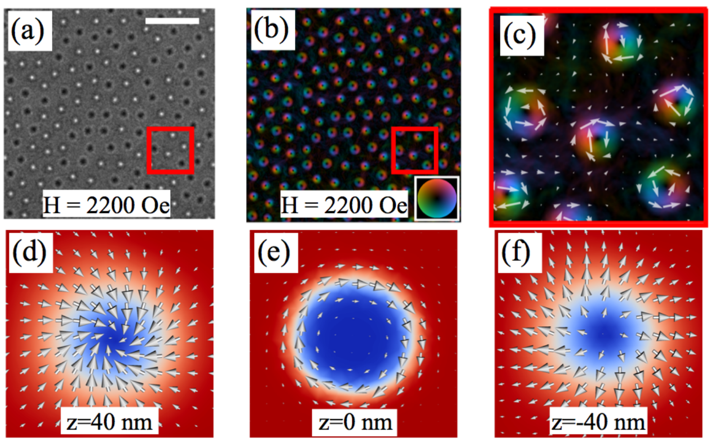

Figure 1. (a-c) Lorentz TEM image of a closed packed lattice of dipole skyrmions in an 80-nm thick Fe/Gd film and (d-f) Numerical simulations of a single dipole skyrmion ($\boldsymbol{S = 1, \gamma = -\pi/2}$) at different depths for an 80-nm thick slab with properties M_S = 400 emu/cm^3, K_U = 4×10^5 ergs/cm^3, $A = 5 \times 10^{-7}$ erg/cm. The bar in (a) is 1μm. Figure is adapted from results in [4].

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