Magneto-Ionic Control of Spin Textures and Interfaces

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Magneto-ionics has shown promise to address the energy challenges in nanoelectronics, as materials properties may be manipulated by the application of an electric field through controlled motion of ions. Here we illustrate magneto-ionic control of Dzyaloshinskii–Moriya interaction, chiral spin textures, exchange bias, and their potential applications in 3-dimensional information storage.

***Index Terms*—Magneto-ionics, chiral spin texture, exchange bias, nanowire networks.**

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I. Introduction

Magneto-ionics (MI) has shown promise for energy-efficient magnetic memory and neuromorphics, where ionic migration can be used to achieve atomic scale control of interfaces in magnetic nanostructures, and in turn modulate a wide variety of functionalities. Conventionally, MI via electrostatic modulation of carrier distribution is limited to the material / electrolyte interfaces [1-3]. Other studies have shown that certain MI effects via electrochemical means may extend beyond the interface [4-8], offering new opportunities to modulate materials properties.

II. DMI and Spin Textures

Using spin-polarized low-energy electron microscopy (SPLEEM), we have discovered that certain chemisorbed species on ferromagnet (FM) surfaces may induce Dzyaloshinskii–Moriya interaction (DMI) [9, 10], a handle to introduce topology into nanomagnets. In a model system of Ni/Co/Pd/W(110) multilayers, where the effective DMI can be tuned by controlling the Pd layer thickness, we have observed a chemisorption-dependent evolution of domain wall chirality. The induced DMI is due to the electric dipole moment as a result of the charge transfer at the DMI interface. This has enabled direct tailoring of skyrmion winding number via oxygen chemisorption. We have also demonstrated a sensitive and reversible chirality switching of magnetic domain walls via hydrogen chemisorption / desorption [10].

Furthermore, we have demonstrated a field-free method to write/delete magnetic skyrmions at room temperature, via hydrogen chemisorption/desorption cycles on Ni/Co/Pd/W(110) [11]. The spin structures of the written skyrmions are resolved to be hedgehog Néel-type via magnetization vector mapping using SPLEEM (Fig. 1). The skyrmion creation/annihilation is attributed to the hydrogen-induced magnetic anisotropy change on FM surfaces.

In another study, we have observed an ultrasensitive chirality switching in $(Ni/Co)_n$ multilayer induced by capping with only 0.22 monolayer of Pd [12]. Using SPLEEM, we monitor the gradual evolution of domain walls from left-handed to right-handed Néel walls and quantify the DMI induced by the Pd capping layer (Fig. 2). We also observe the chiral evolution of a skyrmion during the DMI switching, where no significant topological protection is found as the skyrmion winding number varies. This corresponds to a minimum energy cost of < 1 attojoule during the skyrmion chirality switching.

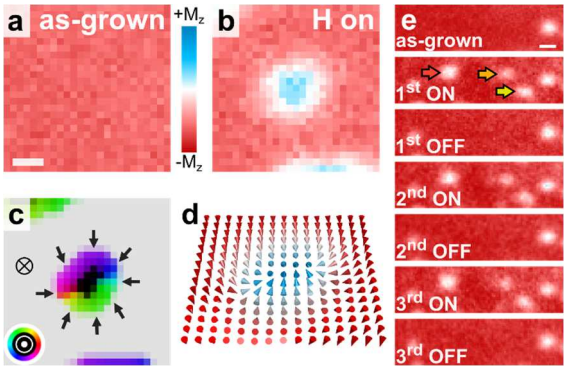

Fig. 1. Hydrogen-induced reversible writing/deleting of skyrmions. (a,b) SPLEEM image of Ni/Co/Pd/W(110), before/after the hydrogen exposure, showing hydrogen-induced skyrmion creation. Scale bar is 100 nm. (c) Compound SPLEEM image resolving the bubble-like domain in panel b as a skyrmion. (d) Experimentally determined arrow-array representation of panel c. (e) SPLEEM images showing reversible skyrmion writing/deleting over three hydrogen on/off cycles (indicated by the arrows), scale bar is 200 nm.

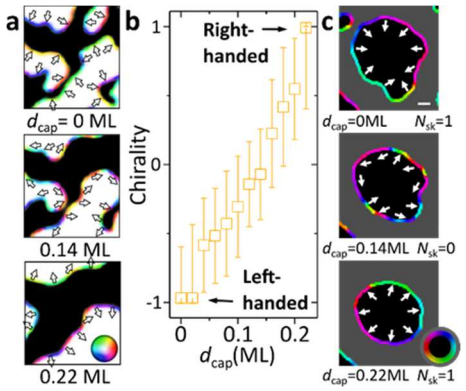

Fig. 2. The chirality and skyrmion number evolution induced by sub-monolayer Pd capping layer. (a) Compound SPLEEM images of $(Ni/Co)_n$/Pd/W(110) with various Pd capping layer thickness d_{cap}, showing a gradual chirality switching from left- to right-handedness. (b) The quantified chirality varies as a function of d_{cap}. (c) The compound SPLEEM images highlighting the chirality and skyrmion number N_{sk} evolution of a skyrmion bubble.

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III. Exchange Bias

The MI effects can be readily integrated into solid state MI devices, where the ionic motion can be further controlled by an electric field [13, 14]. We have investigated electric field enhanced exchange bias in Gd/NiCoO via MI control of the antiferromagnetic oxide, even though neither component alone is FM at room temperature [15]. The exchange bias is enhanced by up to 35% after a voltage conditioning and subsequently reset with a field cooling (Fig. 3). These effects are caused by the presence of a redox-induced interfacial FM NiCo layer, which further alloys with the Gd layer upon field cooling and voltage application. Ion irradiation is used to alter the interfacial microstructure and in turn the EB [16]. These results highlight the viability of the solid-state MI approach towards electric control of exchange bias.

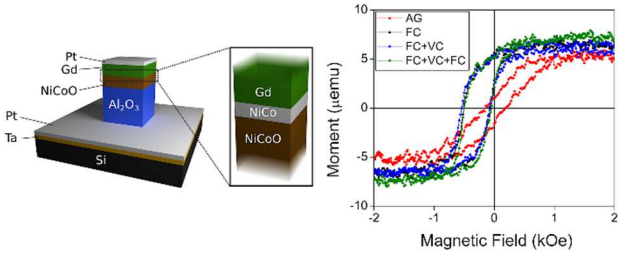

Fig. 3. (Left) Layer structure of the samples. Inset shows a magnified view of the NiCoO/Gd interface. (Right) Hysteresis loops of a Gd/$Ni_{0.50}Co_{0.50}O$ sample in the as-grown (AG) state, after field cooling (FC), after voltage conditioning (FC+VC), and after a second field cooling (FC+VC+FC).

IV. 3D Nanomagnetics

The MI effects are relevant for 3-dimensional (3D) information storage as a potentially contactless way to address spin textures, such as the envisioned racetrack memory [17, 18]. Interconnected nanowire networks offer an exciting model platform to explore 3D nanomagnetism, as we recently demonstrated (Fig. 4a) [19]. Magnetization reversal mechanisms in Co networks are captured by the first-order reversal curve (FORC) method, which illustrate the evolution from strong demagnetizing dipolar interactions to intersections-mediated domain wall pinning and propagation, and eventually to shape-anisotropy dominated magnetization reversal (Fig. 4b). By varying the applied magnetic field strength, orientation, and sequence, it is possible to selectively address a certain subset of the nanowire networks, encode digital information into their magnetic state, and propagate it through the networks for potential 3D magnetic memory and logic applications. Such networks of magnetic nanowires also have the potential to implement repeatable multi-state memristors in neuromorphic circuits, due to the expected discrete nature of domain wall motion through the intersecting networks. Interestingly, another random configuration of metallic nanowire networks has found applications in deep-submicron particulate filtration, relevant to combatting COVID-19 and air pollution [20, 21].

Our findings illustrate potentials for designing a variety of energy-efficient skyrmionic and magneto-ionic devices.

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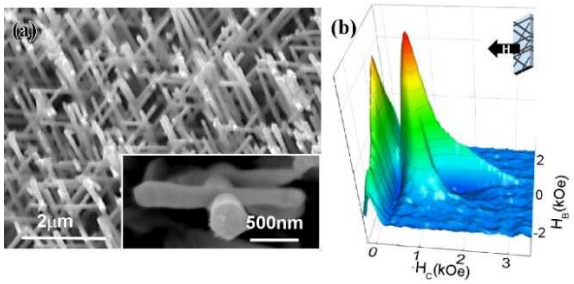

Fig. 4. (a) SEM image of Cu networks. (b) FORC distribution of Co networks.

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