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Magnetic Structure Characterization Over Multiple Length Scales

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Magnetic materials are important functional materials and find broad applications in modern technologies, such as information storage, spintronics, electric motors, generators, transformers, sensors, actuators, transducers, energy harvesters, etc. The properties and functionalities of magnetic materials are determined by their underlying magnetic structures and domain evolutions under externally applied magnetic fields. Magnetic structures form over multiple length scales. The characterization of magnetic structures over multiple length scales plays an essential role in advancing the understanding of structure-property-processing relationships of magnetic materials. Direct observation of dynamic domain evolution under in-situ external magnetic field is essential in understanding the magnetization processes. Among various magnetic structure characterization techniques, this special topic covers several complementary characterization techniques that help illuminate magnetic phenomena over multiple length scales, ranging from atomic-scale spin configurations and nano-scale structures to meso-scale domains in various magnetic materials. In particular, electron holography and Lorentz microscopy are carried out in transmission electron microscopy mode to characterize magnetic structures at nanoscales, magneto-optical Kerr effect (MOKE) microscopy is employed to characterize magnetic domain structures at the mesoscale above optical resolution limit, and neutron scattering assisted by quantitative computational simulation tool is used to characterize magnetic spin configurations at atomistic scale.

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The capabilities of these techniques are demonstrated in various magnetic materials and science areas.

The article “Magnetic nanostructure analysis using electron holography: a review of recent studies of phase separation and planar defects in crystals” by Murakami and Lee presents recent examples of electron holography and Lorentz microscopy studies of magnetic nanostructures. Operating in transmission electron microscopy mode, electron holography and Lorentz microscopy conveniently complement each other to characterize the magnetic structures at nanoscale. The capability of these techniques is demonstrated by the magnetic structures in hole-doped manganite $La_{0.25}Pr_{0.375}Ca_{0.375}MnO_3$ colossal magnetoresistance material, ferromagnetic spin order stabilized at structurally disordered antiphase boundary in $Fe_{70}Al_{30}$ alloy, and magnetism at grain boundary in Nd-Fe-B permanent magnet. Furthermore, based on the observed critical size for the transition from single domain to multiple domain and the domain wall width, material parameters of magnetic domain wall energy density, exchange stiffness, and magnetocrystalline anisotropy are determined from the nanodomain characterization.

The article “Field-dependent magnetic domain behavior in van der Waals Fe_3GeTe_2” by Phatak et al. presents an in-situ cryo Lorentz transmission electron microscopy study of field-dependent magnetic domain behavior in two-dimensional magnetic van der Waals Fe_3GeTe_2 material. Topologically non-trivial magnetization spin textures are examined. Néel-type stripe domains and skyrmions are formed depending on magnetic field-cooling protocol. Quantitative reconstruction of magnetic induction maps is used in combination with micromagnetic simulations to establish an understanding of the energy landscape that governs the magnetic domain behaviors which can be harnessed for spintronic applications.

In “Magnetization reversal and domain structures in perpendicular synthetic antiferromagnets prepared on rigid and flexible substrates,” Bedanta et al. present a study of magnetization reversal and domain structures in perpendicular synthetic antiferromagnets. Ferromagnetic Pt/Co layers separated by nonmagnetic metallic Ir spacer layers are grown on rigid Si and flexible polyimide substrates, where interlayer exchange interaction of Ruderman-Kittel-Kasuya-Yosida coupling makes the synthetic structures become antiferromagnetic layered materials. MOKE microscopy is employed to simultaneously observe the magnetic domain structure evolution during magnetization reversal and measure the magnetization hysteresis loop, which reveals the effects of ferromagnetic layer number, spacer layer thickness, and strain on the interlayer exchange coupling.

The article “Magnetization reversals of Nd-Fe-B-based magnets with different microstructural features” by Sepehri-Amin et al. presents a study of magnetization reversals of Nd-Fe-B-based permanent magnets. MOKE microscopy is employed for dynamic observation of magnetic domains while applying external magnetic fields to correlate the magnetization reversal processes with different microstructural features in the sintered magnets. The coercivity mechanism is interpreted in terms of domain wall pinning by intergranular phase at grain boundaries, which suggests further exchange decoupling in ultra-fine-grained magnets would lead to larger coercivities close to their theoretical limit.

Finally, “Toward discord: code for simulating continuous spin systems” by Morgan and Ye presents the development of a forward Monte Carlo computational tool to simulate magnetic spin systems with frustrated crystal structures. Complementary single-spin flip and cluster-spin flip algorithms are implemented to simulate the spin configurations and calculate the neutron diffuse scattering patterns and spin-pair correlations. The method is demonstrated for several magnetic systems of various complexities. This forward Monte Carlo method together with the previously developed reverse Monte Carlo method forms a complete computational framework *discord* for simulating frustrated magnetic spin structures at atomistic scale, facilitating quantitative analysis of complex neutron diffuse scattering data.

All titles and authors of the articles published under the topic “Magnetic Structure Characterization Over Multiple Length Scales” in the June 2022 issue (vol. 74, no. 6) of JOM can be accessed via the journal’s page at: http://link.springer.com/journal/11837/74/6/page/1.