2570 Microsc. Microanal. 28 (Suppl 1), 2022
doi:10.1017/S1431927622009795

Advances in Imaging Magnetic Domains in Functional Materials using Lorentz microscopy

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Lorentz transmission electron microscopy (LTEM) is ideally suited for quantitative analysis of magnetic domains at the nanometer length scale. The ability to study both the microstructure and magnetic domain structure simultaneously in functional materials allows for direct understanding of the fundamental role of inhomogeneities in microstructure as well as the effect of shape and size of nanostructures on the magnetic domain behavior. The current state of the art LTEM enabled using aberration correctors allows for imaging down to sub-nanometer scale in field-free conditions. With in-situ LTEM capabilities, the magnetic domain behavior can be studied as a function of external stimuli such as temperature, or applied field, to gain a more detailed understanding of the fundamental physics. In order to obtain the quantitative information about the magnetization of the sample, it is essential to retrieve the phase shift of the electrons. This can be obtained using various methods such as in-line or off-axis electron holography, and more recently using 4D-STEM approaches. In this talk, we will present recent advances in phase retrieval for LTEM using neural-network based approaches. In the first approach, we use automatic differentiation (AD) to solve for the phase from a through-focus series of images and show that we are able to achieve a higher phase sensitivity and spatial resolution than previous techniques as shown in Figure 1 [1]. The second approach relies on using a convolutional neural network (CNN) to directly predict the phase from a given single underfocus LTEM image based on an extensive training dataset.

Topologically non-trivial spin textures such as skyrmions [2,3] present unique opportunities to explore exciting fundamental phenomena such as topological Hall effect as well as novel applications such as skyrmion-based spintronics. The realization of such states in van der Waals ferromagnets opens further opportunities to explore their behavior in the 2D limit and to control their behavior using interfacial interactions such as strain or interfacing with dissimilar materials. In this work, we will present in-situ cryo LTEM imaging of $CrGeTe_3$ under various conditions such as zero field cooling and field cooling process. We will elucidate the nature of the observed magnetic domains to be Bloch-type magnetic domains which are achiral as shown in Figure 2 (a) and (b). Furthermore, we will demonstrate the effect of local strain on the skyrmion lattices in this material as shown in Figure 2(c).

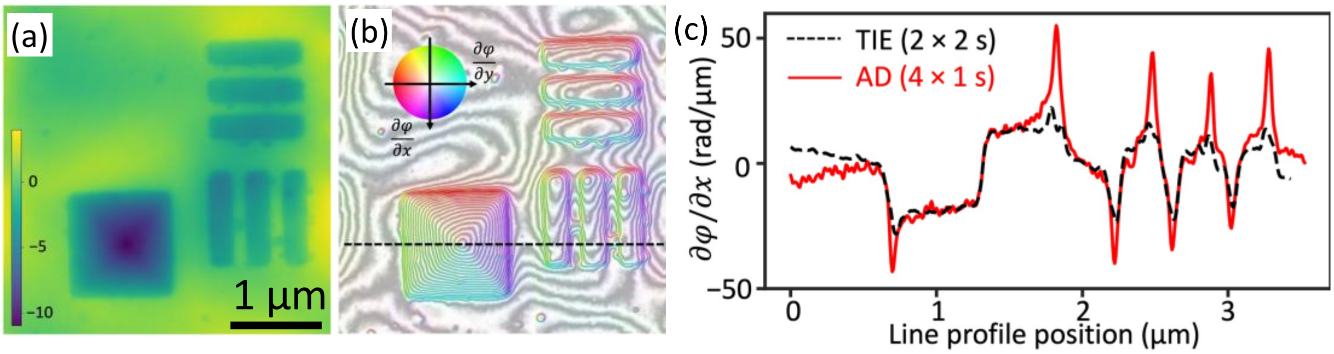

Figure 1. (a) Phase map and (b) magnetic induction map retrieved using AD approach, and (c) a comparison of the phase gradient recovered using the conventional transport of intensity (TIE) method and the AD method. Data demonstrate high spatial resolution achieved for phase reconstruction and magnetic imaging with AD method.

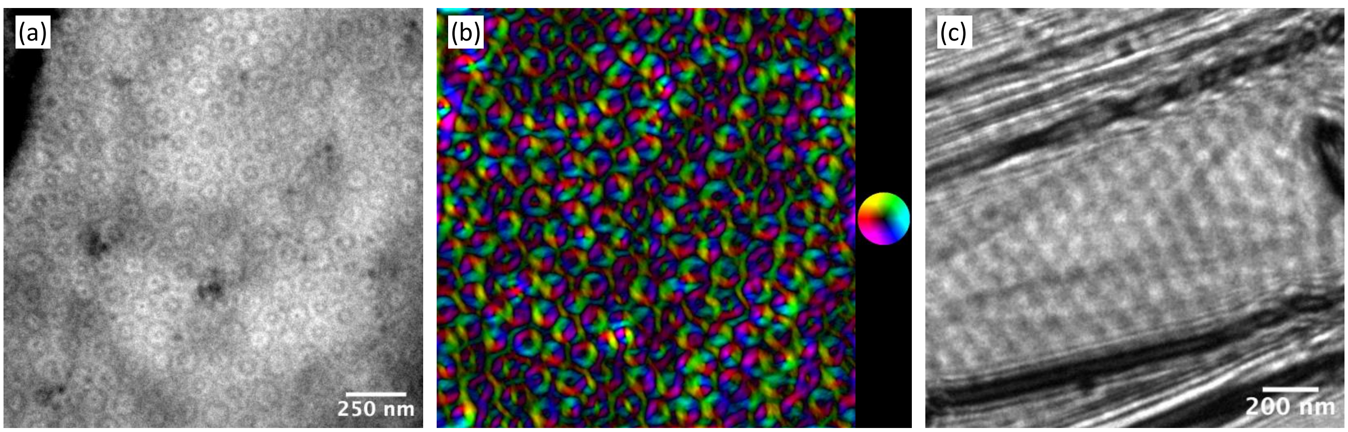

Figure 2. (a) Underfocus LTEM image of $CrGeTe_3$ recorded at 15 K when field-cooled under 600 G applied field, and (b) correspondng reconstructed magnetic induction color map, and (c) a strained region of the sample showing a regular arrangement of skyrmion lattice at 15 K when field-cooled under 400 G applied field.

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[4] This work was supported by U.S. Department of Energy (DOE), Office of Science, Basic Energy Science, Materials Sciences and Engineering Division. Use of Center for Nanoscale Materials was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under contract no. DE-AC02-06CH11357.

https://doi.org/10.1017/S1431927622009795 Published online by Cambridge University Press