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Quantitative characterization of the magnetic properties of manganite thin films using off-axis electron holography

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Detailed local characterization of the magnetic properties of epitaxial perovskite magnetic oxide films is essential for providing a fundamental understanding of structure-magnetism correlations for their applications in spintronic devices. Epitaxial $La_{0.67}Sr_{0.33}MnO_3$ (LSMO) thin films are of great interest as they exhibit colossal magnetoresistance, high spin polarization and a relatively high Curie temperature TC of 370 K. They also provide a highly attractive model system for applications in magnetoelectric devices, for example as bottom electrodes in thin film devices and active magnetic layers in magnetoresistive tunnel junctions. In tunnel junctions, the tunneling rate depends on the relative orientations of the magnetic spins on both sides of the barrier (1). Off-axis electron holography (EH) and Lorentz transmission electron microscopy (TEM) are powerful techniques for characterising magnetic field distributions in materials with high spatial resolution (2). However, the quantitative study of magnetization distributions in LSMO films using off-axis EH is challenging.

Here, we use off-axis EH to measure the magnetic field distribution in an epitaxial 200-nm-thick LSMO film deposited on a Nb-doped $SrTiO_3$ (NSTO) substrate. A cross-sectional specimen was prepared using a dual-beam focused Ga ion beam system (ThermoFisher Helios 440). Surface damage on the lamella was reduced by using low-energy Ar ion milling with an ion energy of below 1 keV (Fischione Nanomill). TEM measurements were performed both at room temperature and at cryogenic temperature using a liquid-nitrogen-cooled TEM specimen holder (Gatan 636) in an aberration-corrected transmission electron microscope operated in Lorentz mode (ThermoFisher Titan 60-300). Off-axis electron holograms were recorded using a direct electron detection camera (Gatan K2 IS). The magnetic contribution to the total recorded phase shift was separated from the mean inner potential contribution by tilting and magnetizing the specimen using the conventional objective lens of the microscope. The projected in-plane magnetisation distribution was calculated from the magnetic contribution to the phase by using a model-based iterative reconstruction algorithm.

Our results suggest that the LSMO film consists of a ferromagnetic layer with a T^C of 339 K adjacent to the NSTO substrate and a paramagnetic layer with a T_C of 279 K above the ferromagnetic layer, as shown in Figure 1. The in-plane magnetisation in the ferromagnetic layer was estimated to be approximately 536 emu/cc. This value is two times larger than the value of 258 emu/cc measured using Superconducting Quantum Interference Device (SQUID) magnetometry, which measures the average magnetization in the entire LSMO film. Our measurements reveal new information about magnetic interactions between different phases in LSMO films and can be used provide an improved understanding of device performance.

References:

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Fig: 1: In-plane magnetic phase images (a-c) and corresponding magnetic induction maps (d-f) of a LSMO film on a NSTO substrate at 290 K, 240 K, 93 K, respectively.

Fig. 1