

Experimental report

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Proposal: 5-54-404

Council: 4/2023

Title: Magnetic lateral distribution of oxide thin film/ nanoparticles designed heterostructures for magnetic switching

Research area: Physics

This proposal is a new proposal

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Samples: Fe₃O₄/SiO₂/SrTiO₃

Instrument	Requested days	Allocated days	From	To
D33	3	2	24/08/2023	26/08/2023

Abstract:

Understanding the mechanisms of magnetization switching in nanosized systems is important for development of novel spintronic devices. In this project, we grow Fe₃O₄ films on nanosphere patterned substrates to achieve magnetization switching by the periodic curvature of the patterned substrate. Growing 30nm Fe₃O₄ thin films on 200nm SiO₂ nanospheres, results in isolated Fe₃O₄ caps. The curvature of the caps affects the lateral correlations between the magnetic domains. In SQUID measurements, we observe differences in the in-plane MH curves which must be related to the geometry of Fe₃O₄ thin films grown on nanosphere-patterned substrate compared to a flat substrate. SQUID measurements, however, give only an average of the magnetic moment over the entire sample surface and cannot reveal the magnetic lateral ordering. Therefore, we propose to measure polarized GISANS to probe the depth-resolved lateral domain profiles of the isolated caps.

Experiment report: Magnetic lateral distribution of oxide thin film/ nanoparticles designed heterostructures for magnetic

The development of new functionalities for memristors is imperative for the enhancement of neuromorphic computing efficiency. In this study, we leverage curvature to engineer novel materials with advanced magnetic functionalities. We have fabricated thin films of ferrimagnetic material (Fe_3O_4) on self-assembled SiO_2 nanoparticles through pulsed laser deposition, thereby achieving nanosized magnetization switching in magnetic thin films. Through the utilization of structural and magnetic characterization techniques including; STEM, GISANS, and XMCD-PEEM, significant variations in domain structuring, interfacial oxidation state, and in-plane vortex state formation in the curved magnetic films have been observed. These findings establish the foundation for curvilinear memristors and demonstrate a new strategy for designing high-performance magnetic oxide interfaces.

To reveal the influence of the nanosphere curvature on magnetic domain structure, polarized GISANS with full polarization analysis was conducted using the D33 instrument. Neutrons were polarized either parallel (+) or anti-parallel (-) to the applied in-plane magnetic field. The GISANS patterns were recorded in four channels: non-spin-flip (NSF) channels (++) and (--) sensitive to in-plane magnetization, and spin-flip (SF) channels (+- and -+) sensitive to out-of-plane magnetization. GISANS measurements were performed at 300 K and 10 K under various applied magnetic fields.

Figure 1(b) shows the 2D GISANS pattern at 300 K for I^{++} channel, measured at an applied field of -1.2 T. The pattern shows a specular peak at $Q_z=0.22 \text{ nm}^{-1}$ with peaks distributed along Q_y gives an insight into the lateral magnetic structure. The positions of the observed peaks along Q_y align with those observed in GISAXS, confirming that the Fe_3O_4 film follows the arrangement of the nanospheres.

At 300 K, a splitting observed between I^{++} and I^{--} as shown in Figure 1(c) may indicate the existence of lateral magnetic correlations. Despite being that the measurement was conducted above the critical angle of Fe_3O_4 (i.e. within the total reflection region), the magnetic inhomogeneities in the Fe_3O_4 film due to the nanospheres curvature, generate a magnetic lateral variation that modulates the scattering intensity in the GISANS channels. At 300K, thermal fluctuations weaken the overall magnetic anisotropy, but they don't completely destroy the lateral spin correlations. This enables the spin asymmetry to exist, particularly in regions where domains are locally enhanced ordering due to the curvature of the nanospheres. The observed splitting aligns with the M(H) curves (Figure 1(a)), indicating that the film keeps coercivity at 300 K, suggesting stable magnetic domains that contribute to the GISANS asymmetry. However, no splitting was observed between the SF channels (I^{+-} and I^{-+}). The absence of SF scattering confirms that there is no out-of-plane magnetization component, meaning that the magnetic moments are confined to the in-plane direction. If structural features dominate the scattering and the magnetic domains are aligned out-

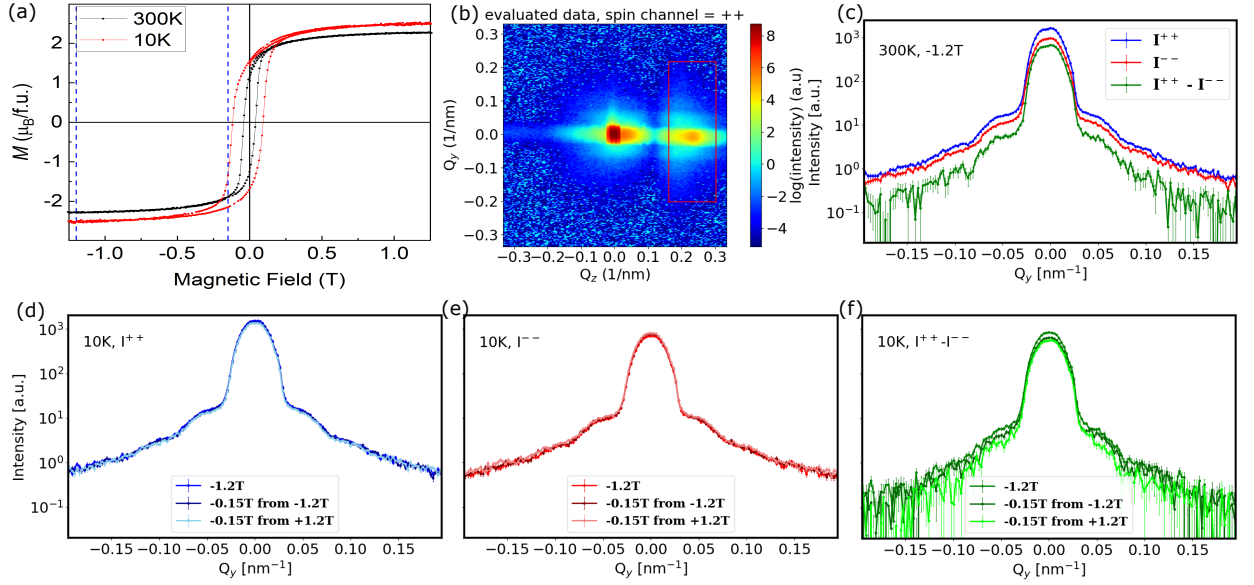


Figure 1: (a) Magnetization vs magnetic field for Fe_3O_4 film deposited on SiO_2 nanospheres on $Nb:SrTiO_3$ substrate at temperatures of 300 K and 10 K with marked lines indicate the magnetic fields at which GISANS measurements were performed. GISANS measurements at room temperature with in-plane magnetic field of -1.2 T: (b) 2D image of I^{++} spin channel with red square marks the integrated intensity area used for (c) I^{++} , I^{--} and $I^{++} - I^{--}$. GISANS measurements at 10 K at different in-plane magnetic fields of -1.2 T and -0.15 T (once from 1.2 T and once from -1.2 T) (d) I^{++} , (e) I^{--} and (f) $I^{++} - I^{--}$.

of-plane, a SF signal will be expected. However, since no SF signal was observed, this strongly supports the conclusion that the magnetization lies entirely with the plane of the film. Additionally, no peaks were observed in the SF channels, further emphasizing an absence of out-of-plane contributions or modulation in the magnetic structure. Figure 1(d-f) presents GISANS patterns measured at 10 K and different fields. The peaks along Q_y in the NSF channels remain at the same positions in comparison to room temperature measurements, indicating that the structural periodicity of the nanospheres and the magnetic Fe_3O_4 layer is preserved upon cooling through the Verwey transition. This suggests no structural rearrangements or morphological changes by temperature variations. Similar to the measurements at 300K, no SF signal was observed, confirming our conclusion that the magnetization lies entirely with the plane of the film.

The GISANS patterns confirm a strong correlation between the lateral magnetic domains of the Fe_3O_4 films and the nanosphere structure, indicating that the magnetic layer conforms to the curved surface geometry. The observed in-plane magnetization distribution, without out-of-plane components, supports our understanding of how curvature influences domain alignment.