Research in Progress

Magnetization Profiles in Nanomaterials

Valeria Lauter and postdoc staff Hailemariam Ambaye at the SNS Magnetism Reflectometer.

A major 2008 upgrade to the Magnetism Reflectometer is enabling dramatically improved studies of nanomaterials. Improvements in background level (reducing interference from other effects), polarization level (degree to which individual neutron spins are aligned), and resolution are enabling researchers to analyze components of the magnetization density of materials at a remarkable resolution of half a nanometer. This advance is providing new insight into how the various atomic-scale magnetic structures interact in different parts of a material. The sensitivity achieved with the enhanced instrument now allows researchers to detect changes in the magnetic state of a layer of material with the thickness of a single unit cell (the smallest bit of a material that preserves its unique structure).

Researchers use polarized neutrons, or those with a magnetic spin in one direction, to determine the magnetic qualities of materials. Polarized neutron reflectometry is being used to study the magnetism at the interfaces between different materials in epitaxial heterostructures based on lanthanum manganese oxide (LaMnO). (An epitaxial structure is a thin sheet or film of a material composed of layers deposited or grown in an orderly fashion so that successive layers are aligned atom by atom, forming a single crystal).

The work is being carried out by the Magnetism Reflectometer research team of lead instrument scientist Valeria Lauter, postdoctoral staff member Hailemariam Ambaye, and others in collaboration with Hans Christen and Michael Biegalski of the ORNL CNMS.

Materials can be ferromagnetic (with individual atomic spins aligned in the same direction, as in a permanent magnet), antiferromagnetic (with atomic spins aligned in opposite directions, so that it has no overall magnetic character), or paramagnetic (exhiting magnetic behavior only in the presence of an external magnetic field). In bulk form, $LaMnO_3$ is a well-known antiferromagnet, so it has no overall magnetic character. However, when $LaMnO_3$ is grown in the shape of a thin film, it can acquire new properties at interfaces because of its proximity to other elements. Previous work on these interfaces has shown enhanced ferromagnetism at the interfaces between $LaMnO_3$ and the paramagnetic insulator, strontium titanium oxide ($SrTiO_3$).

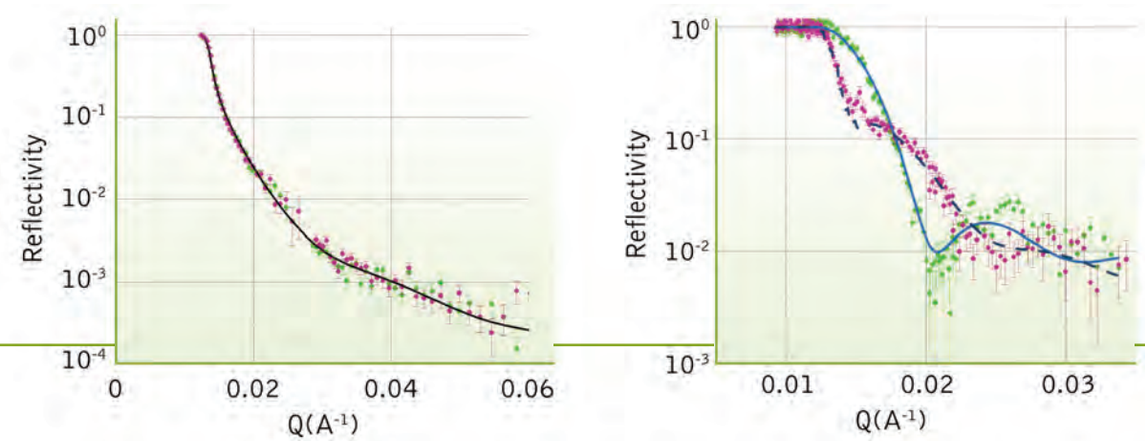

Figure 1a. Neutron reflectivity profiles R+ (green points) and R- (magenta points) as functions of momentum transfer for an $SrTiO_3/LaMnO_3$ bilayer film on $SrTiO_3$, measured with polarized neutrons and an applied magnetic field of H = 1 Tesla, applied in the plane of the film (left, T = 300 kelvin; right T = 5 kelvin). The solid lines correspond to the data using a model with a depth-dependent scattering length density.

Preliminary results have revealed that the observed magnetism depends on the stacking order of atomic layers at the interface between the two materials. (Different types of interfaces can be formed using pulsed-laser deposition.) Neutron reflectometry can be used to determine the magnetic depth profile of different epitaxial structures with a resolution of less than a nanometer. "The magnetization profile obtained from the reflectometry experiment (see Figure 1a) will provide information that cannot be obtained using any other measurements," Lauter says.

Additional promising nanomaterials research was conducted by Sunil Sinha (University of California–San Diego) and Elizabeth Blackburn (Birmingham University, UK). The team used neutrons to map out the magnetization at the interface of the ferromagnetic and antiferromagnetic layers in the prototypical system (Py/CoO) and observed how the magnetization changes as the material enters the exchange biased state (Figure 2). When an exchange-coupled bi-layer film of a ferromagnet and an antiferromagnet is cooled in an external magnetic field through the ordering temperature of the antiferromagnet, an exchange bias—a shifting of the hysteresis loop—is observed. "Although this effect has already been exploited to develop several new industrial applications using thin film materials, a detailed microscopic understanding of the physical mechanism underlying this effect has proved elusive," Lauter says. The goal of these studies is to search for traces of pinned magnetization, which is thought to be responsible for the observed magnetic behavior.

The epitaxial film imposes an elastic strain (temporary displacement of atomic positions) on the SrTiO substrate. In the course of the experiments, an unexpected effect of this strain was observed below the structural phase transition temperature (the temperature at which the preferred arrangement of atoms within a material changes, ~105 kelvin in this case). "It was observed that the domain state in the substrate can be altered by application of a magnetic field to a magnetic film, and neutron reflectometry has been shown to be sensitive to the resulting minute changes in the surface," Lauter says (see Figure 1b). The research team is continuing to investigate this fascinating and previously unreported effect.

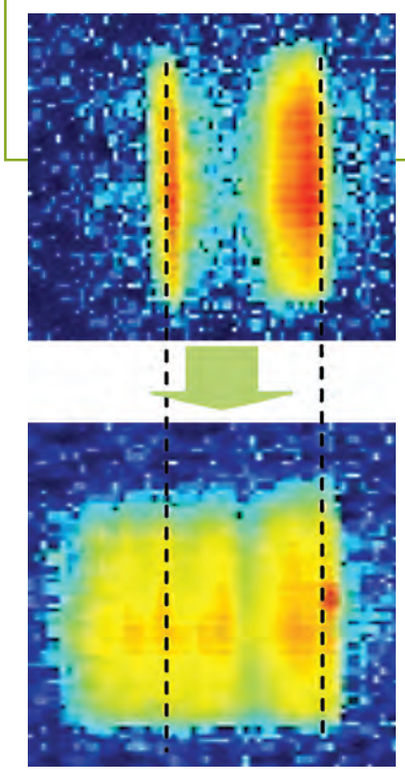

Figure 1b. Experimental intensity maps of incident and reflected neutrons integrated over neutron wavelengths from 2 to 5 angstrom. The dashed lines correspond to the positions of the reflected (left) and the incident (right) intensities at temperatures of 300 kelvin (top) and 5 kelvin (bottom). Drastic changes in the profiles of reflected neutrons give evidence of structural modifications at temperatures below the substrate's phase transition.

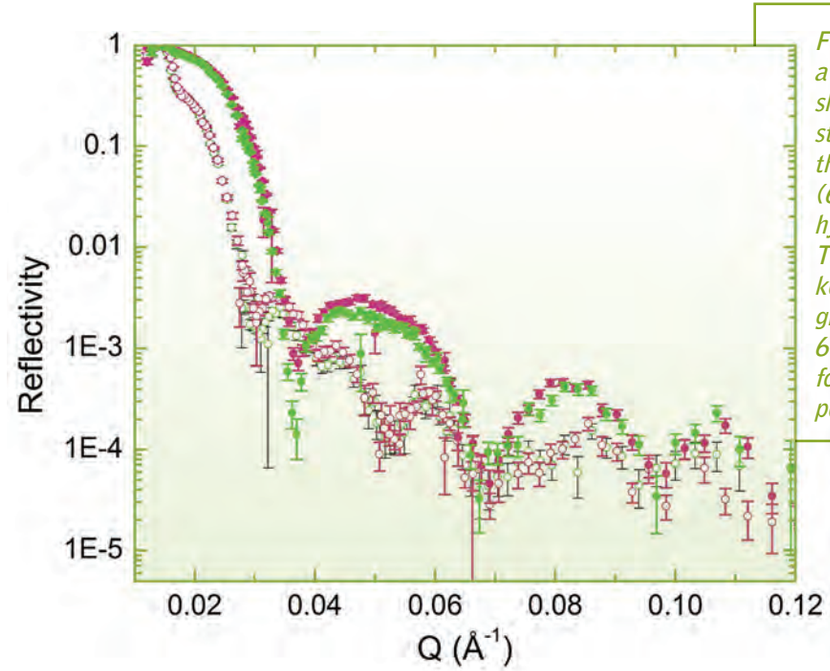

Figure 2. Reflectivity data for a Py/CoO thin film material showing results for the normal state (room temperature) and the exchange-biased state (6 kelvin). The inset shows the hysteresis loop for this sample. The data were taken at 300 kelvin (green solid for R+ and green open points for R-) and 6 kelvin (magenta solid point for R+ and magenta open points for R-).