MAGNETIC DOMAINS IN CO-SIO$_2$ MULTILAYER TUNNEL JUNCTIONS

In the ongoing search for sensors for magnetic recording applications, recent research has focussed on materials that exhibit spin-dependent tunneling. These systems are comprised of metallic, ferromagnetic particles or of layers that are well separated from each other by an insulating material. Magnetoresistance (MR) from spin-dependent tunneling was first reported for granular metal/insulator films in 1972 and for Co/Ge/Fe trilayer junctions in 1975. The effect arises because the tunnel conductance is minimum when the particle or layer moments are aligned antiparallel. Flipping the spin of the conducting electron, with its attendant energy cost, reduces the tunneling between particles or layers.

From a magnetic recording perspective, the objective is to maximize the change in the resistance while minimizing the active field range. Multilayer tunnel junctions exhibit pronounced field sensitivity, but the insulating barrier layers are susceptible to pinholes that connect the ferromagnetic layers. In contrast, granular films with small ferromagnetic particles are easy to fabricate by co-deposition of a metal with an immiscible insulator. However, the saturation fields for the MR are large and the approach to saturation is gradual because the particles are magnetically isolated.

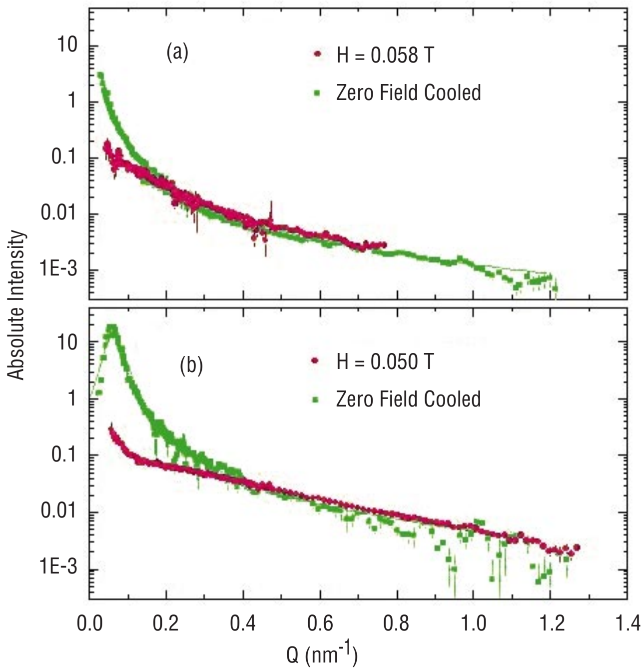

FIGURE 1. Circular average of SANS data for the [SiO$_2$(3.0 nm)|Co(1.6 nm)]$_{60.5}$ multilayer (a) and the Co(0.4)/SiO$_2$(0.6) granular film (b) at 15 K. The ZFC data for the film are from a sector average at 45°. Data fits are shown as lines.

Desirable characteristics of both magnetic tunnel junctions and the granular films are combined in discontinuous metal/insulator multilayers, which represent a new class of spin tunneling devices. These hybrid systems are prepared by alternately sputtering two immiscible materials, such as Co and SiO$_2$, onto a substrate. Since the metal does not wet the insulator, the ferromagnet breaks up into nanoparticles during growth. Transmission electron microscope images and x-ray diffraction data of Co/SiO$_2$ multilayers reveal that the Co forms either individual particles with diameters of 2.5 nm or chains composed of touching particles. In contrast to granular films, the MR of these hybrid structures is maximum at a smaller magnetic field, which is useful for applications. However, the dependence of the MR on small magnetic fields is not consistent with a simple picture of the magnetic moments of individual particles changing independently. Instead it is believed that the smaller particles are magnetically coupled to form larger magnetic domains. Neutron scattering experiments characterize the magnetic structure (i.e., the magnetic correlation length) associated with the MR maximum. This correlation length is required to model the MR mechanism.

Initial neutron reflectivity studies of a [SiO$_2$(3.0 nm)|Co(2.0 nm)]$_{24.5}$ multilayer with the sharpest MR showed that the Co spins are randomly oriented along the growth direction at fields near the coercive field, H_C, where the magnetic hysteresis loop crosses the field axis (i.e., zero net moment). However, the average size of the magnetic domains across the sample plane is substantially larger (0.1 – 0.5 µm) than the average size of the Co particles. A multilayer with a smaller nominal Co thickness, [SiO$_2$(3.0 nm)|Co(1.6 nm)]$_{60.5}$, showed no in-plane magnetic ordering within the sensitivity of the reflectivity experiments. Small angle neutron scattering (SANS) measurements of this multilayer and a 0.5 µm thick Co(0.4)/SiO$_2$(0.6) granular film were thus undertaken to probe smaller lengthscales. These experiments indicate that the correlation lengths at H_C are larger for the discontinuous multilayer than for the granular film. In addition, data obtained for both samples after cooling in zero field (ZFC) indicate that the Co particles have an intrinsic magnetic interaction.

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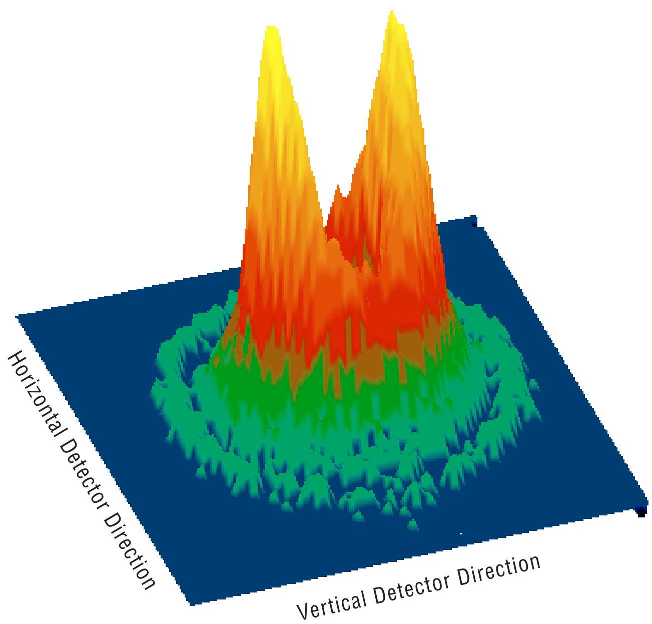

FIGURE 2. SANS image from a Co(0.4)/SiO$_2$(0.6) granular film after cooling from room temperature to 15 K in zero field.

With the exception of the ZFC data for the granular film (Fig. 2), all of the data were circularly symmetric and could be averaged about the center of the detector. Figure 1 (a) shows the average magnetic intensity at 15 K plotted as a function of the wavevector Q for the discontinuous multilayer at H_C = 0.058 T (red circles) after saturation in a 0.5 T field. The Lorentzian fit to these data gives a magnetic correlation length of 10 ± 2 nm, which is of the order of the size of the Co nanoparticle chains.

For comparison, the coercive field data (red circles) for the granular film are shown in Fig. 1 (b). These data fit to a linear combination of two squared Lorentzians, which is a functional form often found for scattering from disordered magnets. The dominant term gives a short correlation length of approximately 1.7 ± 0.5 nm, which is smaller than the 4 nm spherical particle size in the granular film. For both the granular film and the discontinuous multilayer, the static and/or dynamic magnetic domains at the coercive field appear to be limited to the individual Co particles. The dramatic contrast in the MR curves for the discontinuous multilayer and the granular film could be a consequence of the difference in the electron-scattering surface area (i.e., the granular film has smaller particles and domains and thus has more scattering surfaces).

The demagnetization process for both the film and the multilayer, however, is very sensitive to field preparation conditions. Figure 1 (a) also shows the average magnetic intensity of the discontinuous multilayer at 15 K after cooling in zero field from room temperature (green squares). These data yield a correlation length of 30 ± 1.5 nm. The act of cooling the multilayer apparently induces interparticle interactions that stabilize domains larger than a single Co nanoparticle.

Figure 2 shows the scattering pattern for the granular film after cooling to 15 K in zero field from room temperature. The intensity is asymmetric with maximum intensity along the vertical axis. These data suggest that the Co moments are preferentially aligned along the horizontal axis. However, this spin anisotropy axis is not evident from magnetization and resistivity data.

The sector average in Fig. 1 (b) further reveals that the ZFC data have a sharp peak at Q = 0.0605 nm^{-1}. The data fits suggest that the ZFC structure for the granular film is comprised of magnetic domains separated by an average distance of 104 ± 1 nm in the film plane. Despite their small size, the Co particles interact with each other upon cooling in zero field to form a well-ordered magnetic state.

The observed difference between the magnetic domain formation in discontinuous spin-tunneling multilayers and granular films is essential to the understanding of their contrasting MR properties. Future studies will focus on the temperature and field evolution of the domains to optimize the performance of these films and multilayers as magnetic sensors.