MAGNETIC PROFILES IN FERROMAGNETIC/SUPERCONDUCTING SUPERLATTICES

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The interplay between ferromagnetism and superconductivity has been of longstanding fundamental research interest to scientists, as the competition between these generally mutually exclusive types of long-range order gives rise to a rich variety of physical phenomena. A method of studying these exciting effects is by investigating artificially layered systems, i.e. alternating deposition of superconducting and ferromagnetic thin films on a substrate, which enables a straight-forward combination of the two types of long-range order and allows the study of how they compete at the interface over nanometer length scales. While originally studies focused on low temperature superconductors interchanged with metallic ferromagnets, in recent years the scope has broadened to include superlattices of high T_c superconductors and colossal magnetoresistance oxides. Creating films where both the superconducting as well as the ferromagnetic layers are complex oxide materials with similar crystal structures (Figure 1), allows the creation of epitaxial superlattices, with potentially atomically flat and ordered interfaces.

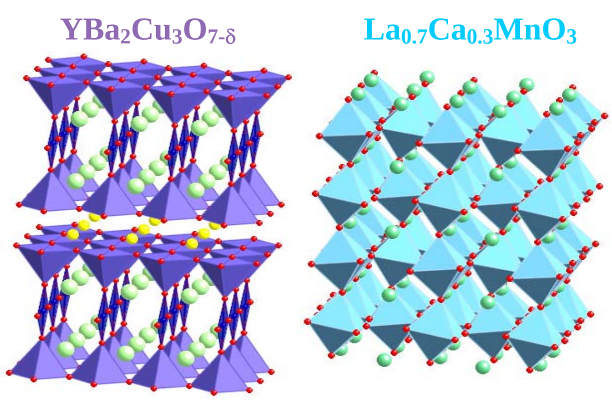

Figure 1: Models of the crystal structure of $YBa_2Cu_3O_{7-\delta}$ and $La_{0.7}Ca_{0.3}MnO_3$

Additionally, owing to their moderate carrier density of 10^{19}–10^{22} cm^{-3}, inhomogeneous charge distributions can be expected within a distance of a few unit cells from an interface. Since the physical properties of these complex oxides depend strongly on the charge carrier doping, this opens up a wide variety of different interactions between dissimilar complex oxides.

Motivated by these arguments the group of Jacobo Santamaria (GFMC, Departamento Fisica Aplicada III, Universidad Complutense de Madrid, 28040 Madrid, Spain) created and started investigating heterostructures of ferromagnetic $La_{0.7}Ca_{0.3}MnO_3$ / superconducting $YBa_2Cu_3O_{7-\delta}$ deposited on $SrTiO_3$. The high degree of spin polarization of the $La_{0.7}Ca_{0.3}MnO_3$ conduction band additionally makes this system a good candidate for the search of novel spin dependent effects, which could lead to the creation of a spintronic devices based on magnetoresistance (MR) effects associated with the accumulation and transport of spin polarized electrons. In initial studies of the superconducting properties of series of heterostructures with varying thicknesses of either the $La_{0.7}Ca_{0.3}MnO_3$ or $YBa_2Cu_3O_{7-\delta}$ layers, proximity effects were detected evidenced by a depression of the superconductivity [1,2].

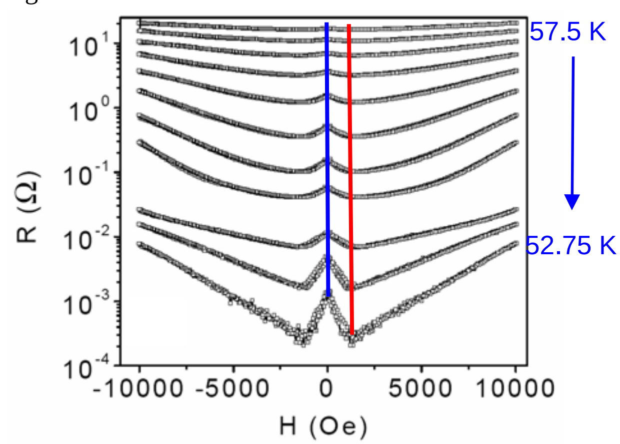

Figure 2: The resistance as a function of field for decreasing temperature around the onset of superconductivity for a $La_{0.7}Ca_{0.3}MnO_3$ (40 u.c.)/ $YBa_2Cu_3O_{7-\delta}$ (15 u.c.)/ $La_{0.7}Ca_{0.3}MnO_3$(40 u.c.) trilayer.

More recently, Santamaria's group observed a novel magnetoresistance (MR), in excess of 1000%, for heterostructures with only a limited number of bilayer repetitions [3]. While this effect is reminiscent of the giant magnetoresistance (GMR) effect typically measured in magnetic superlattices [4], the MR discussed here is only observed when $YBa_2Cu_3O_{7-\delta}$ is in the superconducting state. Figure 2 shows the measured resistance as a function of applied field for various temperatures close to the superconducting transition temperature of $YBa_2Cu_3O_{7-\delta}$. For lower temperatures, peaks in the resistance occur at moderate fields. Comparison with SQUID magnetometry measurements of the magnetization showed that the peaks in the resistance occur close to the coercive fields. Additionally, the magnetization curves show an unusual stepped behavior.

In order to explore the reason for this stepped behavior and gain insight into the origin of the magnetoresistive behavior, polarized neutron reflectivity (PNR) experiments were performed on the POSY1 instrument at IPNS. With these experiments the magnetization of the individual $La_{0.7}Ca_{0.3}MnO_3$ layers was determined as a function of applied magnetic field for various temperatures.

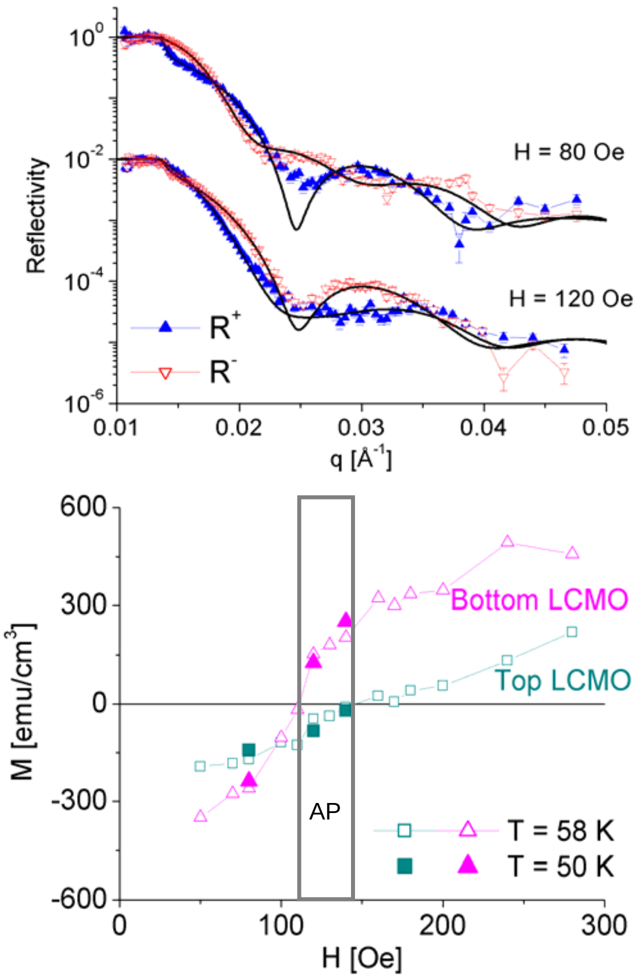

Figure 3: Top: Polarized neutron reflecitivity data for the $La_{0.7}Ca_{0.3}MnO_3$ (40 u.c.)/ $YBa_2Cu_3O_{7-\delta}$ (15 u.c.)/ $La_{0.7}Ca_{0.3}MnO_3$(40 u.c.) trilayer at two applied fields at T = 58K. Bottom: Magnetization of the individual LCMO layers as a function of applied field as determined from the fits of the PNR data. The gray box marks where antiparallel (AP) alignment was detected.

Figure 3 shows how the field dependence of the magnetization of the two $La_{0.7}Ca_{0.3}MnO_3$ layers is quite different. The bottom $La_{0.7}Ca_{0.3}MnO_3$ has a larger magnetization and therefore has a coercive field (where M=0) that is low than that of the top layer. This difference in coercive fields of the two layers, creates a field region where the two layers are aligned antiparallel to each other. Similar results were obtained for a second sample, which had four $La_{0.7}Ca_{0.3}MnO_3$ spaced by three $YBa_2Cu_3O_{7-\delta}$ layers, (Figure 4). Here the bottom $La_{0.7}Ca_{0.3}MnO_3$ layer has a larger magnetization and is aligned aniparallel to the other three for a limited field region. The reason for the variation of the saturation magnetization of the LCMO layers, which causes the variations in switching behavior, was determined with other PNR measurements on similar superlattices [5]. It was found that at the $La_{0.7}Ca_{0.3}MnO_3/YBa_2Cu_3O_{7-\delta}$ interface the magnetization of the $La_{0.7}Ca_{0.3}MnO_3$ was suppressed over a length scale of the order to 1nm, likely due to charge transfer across the interface. This effect would influence the bottom $La_{0.7}Ca_{0.3}MnO_3$ layer less, as it is grown directly on the substrate, therefore retains a magnetization that is close to that of the bulk material.

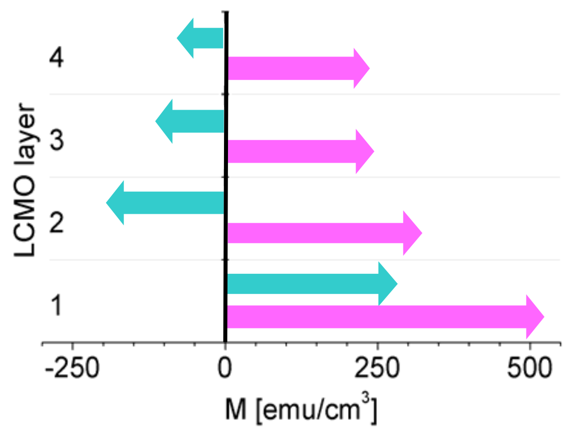

Figure 4: The magnetization of the four LMCO layer in a saturating field (pink) and close to the coercive field (green) determine with polarized neutron reflectivity for a $[La_{0.7}Ca_{0.3}MnO_3$ (40 u.c.)/ $YBa_2Cu_3O_{7-\delta}$ (7 u.c.)]x3.5 superlattice.

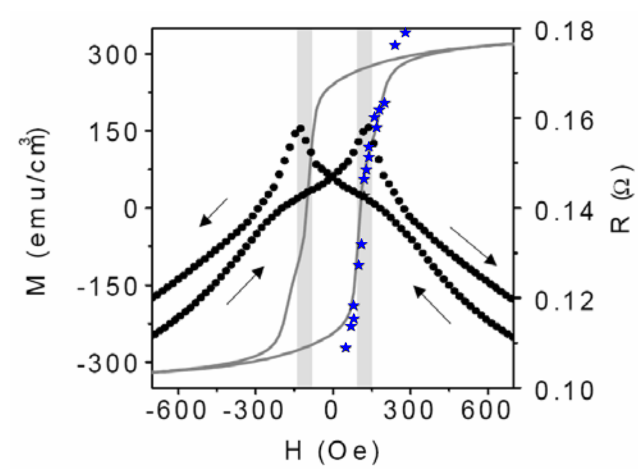

Figure 5: SQUID magnetization M (solid line), resistance R (filled circles) and, PNR magnetization (blue stars) for the $La_{0.7}Ca_{0.3}MnO_3$ (40 u.c.)/ $YBa_2Cu_3O_{7-\delta}$ (15 u.c.)/ $La_{0.7}Ca_{0.3}MnO_3$(40 u.c.) trilayer as a function of applied field. The gray areas mark where antiparallel alignment was detected, which coincides with the peak in R and step in M.

These results were crucial to the understanding of the MR behavior because it is exactly in the field region where antiparallel alignment occurs, that the peak in the magnetoresistance is at its maximum (Figure 5). This also means that the ordering temperature for the superconducting YBCO is suppressed more for antiparallel (blue line in Figure 2) then for parallel alignment (red line in Figure 2). Considering only the proximity effect, the superconductivity depression should be larger with a parallel than with an antiparallel orientation, as has been observed for metallic systems [6]. Our results indicate that spin imbalance [7] in the superconductor due interactions with the ferromagnet is dominating the behavior in these complex oxide films [3].

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