Superconducting Transition Temperature in YBa$_2$Cu$_4$O$_8$/La$_{2/3}$Ca$_{1/3}$MnO$_3$/YBa$_2$Cu$_4$O$_8$ Heterostructure

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Abstract: YBa$_2$Cu$_4$O$_8$/La$_{2/3}$Ca$_{1/3}$MnO$_3$/YBa$_2$Cu$_4$O$_8$ (Y-124/LCMO/Y-124) heterostructure was prepared by facing-target sputtering technique. The oscillatory superconducting transition temperature was observed when the thickness of LCMO $d_L$ is larger than critical thickness $d_{LCR}$. The metal-insulator transition temperature can only be detected at $d_L > d_{LCR}$. The dependence on the spacer layer in LCMO/Y-124 systems suggests strongly the interplay of ferromagnetic and superconducting couplings.

Key words: high-$T_C$ films; colossal magnetoresistance; heterostructure; interlayer coupling; rare earths

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The possibility to study proximity effects between layers with dissimilar intrinsic properties, such as superconductivity and ferromagnetism, has initiated much research activity$^{[1-5]}$. For ferromagnetic (F) layers sandwiched between superconducting (S) layers it is expected that superconducting transition temperature ($T_C$) decreases monotonically with increasing magnetic layer thickness. Wong et al$^{[6]}$ showed a non-monotonic dependence of $T_C$ as a function of Fe layer thickness in V/Fe superlattice with fixed V thickness. The possibility for oscillation of $T_C$ as a function of ferromagnetic layer thickness in S/F multilayer was demonstrated theoretically$^{[7]}$. A critical thickness of ferromagnetic barrier, above which there is no overlapping of superconducting wave functions and hence zero Josephson current, is predicted by Kuplevakhskii and Fal'kovich$^{[8]}$. Buzdin et al$^{[9]}$ reported oscillation of critical current of the junction with ferromagnetic barrier thickness. Experiments on low $T_C$ Pb-Fe-Pb junctions by Claeson indicated a critical thickness of 0.5 nm$^{[10]}$. Owing to structural similarity of two classes of perovskite compounds, high $T_C$ superconductor (HTS) and colossal magnetoresistance (CMR) ferromagnet, unique combination of the two oxide layers is possible. Radovic et al$^{[11]}$ suggested that the unusual effects predicted that is the oscillatory $T_C$ with changing thickness of ferromagnetic layer should be much more pronounced in S/F superlattices with high $T_C$ and short coherence length superconductor. Kasai et al$^{[12]}$ reported the observation of supercurrents in trilayer junctions with a 500 nm thick La$_{0.7}$Ca$_{0.3}$MnO$_3$ ferromagnetic barrier. Recently, Holden et al$^{[13]}$ investigated ellipsometric measurements of far-infrared dielectric properties of YBa$_2$Cu$_3$O$_7$/La$_{2/3}$Ca$_{1/3}$MnO$_3$ superlattices.

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Their results provided clear evidence that free-carrier response is strongly suppressed in these structures as compared to the one in pure YBa2Cu3O7 and La2/3Ca1/3 MnO3 films.[12]. Pena et al.[31] found experimental evidence for coupling between superconducting layers through ferromagnetic spacer in YBa2Cu3O7/La2/3Ca1/3 MnO3 superlattices consistent with long-range F/S proximity effect.

In our previous work, we[14] found that the \( T_c \) of YBa2Cu4O8 layer was strongly suppressed by ferromagnetic La2/3Ca1/3 MnO3 layers due to magnetic proximity effect in La2/3Ca1/3 MnO3/YBa2Cu4O8/La2/3Ca1/3 MnO3 sandwiches. In this paper, a complex \( T_c \) oscillation phenomena for YBa2Cu4O8 (Y-124)/La2/3Ca1/3 MnO3 (LCMO)/Y-124 heterostructure was reported. Here, Y-124 was chose only because it is much more stable than YBa2Cu3O7 in different oxygen environments.

1 Experimental

Heterostructure was fabricated on (001) SrTiO3 (STO) single crystal substrates from pure LCMO and Y-124 targets under a range of conditions by facing-target sputtering technique[15–17]. The deposition rate was 0.05 nm·s\(^{-1}\) for LCMO layer and 0.075 nm·s\(^{-1}\) for Y-124 layer. The resistance as a function of temperature was measured by standard four-probe technique with CIP (current in plane) geometry and the distance between voltage contacts was fixed at 6 mm. The magnetic moment of the samples as functions of temperature and applied magnetic field was measured by utilizing a vibrating sample magnetometer. During the measurements, a magnetic field was applied parallel to the film surface. A small nonhysteretic contribution from the STO substrate was eliminated by separately measuring its di magnetic response.

2 Results and Discussion

Fig. 1 shows temperature dependence of relative resistivity \( \rho/\rho_{100\,K} \) and its temperature coefficient \( \left( d\rho/\rho_{100\,K}\right)/dT \) of Y-124 (75 nm)/LCMO (75 nm)/Y-124 (75 nm) film. The resistivity curve shows the metal-insulator transition of LCMO layer at high temperature, and the cross point at low temperature arises from superconducting transition of Y-124 layers. The metal-to-insulator transition temperature, \( T_{MI} \) and \( T_c \) are defined as the peak points in the differential curve as shown in Fig. 1.

The hysteresis loops of Y-124 (75 nm)/LCMO (75 nm)/Y-124 (75 nm) film are shown in Fig. 2 with the magnetic field applied parallel to the layers. Magnetization loops at 120 K shows a saturation field of 80000 A·m\(^{-1}\), and resembles that of a single LCMO film[18]. The sample displays a characteristic superconductinglike hysteresis loop below \( T_c \), and the flattened slope probably results from a small stray field due to the magnetic layer when \( H > 0 \).

\( T_{MI} \) of as-deposited Y-124/LCMO/Y-124 sandwiches are plotted against the thickness of LCMO layer \( d_L \) in Fig. 3. \( T_{MI} \) is independent of its thickness for films with thick spacer layer. Degradation of \( T_{MI} \) was found on films with thin LCMO layer. Extrapolation gives critical thickness \( d_L^{CR} \), below which \( T_{MI} \) can not be detected. \( d_L^{CR} \) is about 5.5, 7.0 and 9.0 nm for \( d_y = 7.5, \) 45 and 75 nm respectively. Here, \( d_y \) is the thickness of YBCO layer. Jin et al.[19] studied the effects of film thickness for La0.67Ca0.33MnO3 film, and concluded that 100 nm is a promising thickness for CMR effect. Rao and co-workers[20] accessed similar issue, and observed a significant enhancement of strain and an accompanied weakening of ferromagnetic order in ultra-thin film. Sun et al.[21] found a sharp
The interlayer coupling of superconducting Y-124 thin films through ferromagnetic LCMO layer was investigated from transport properties of Y-124/LCMO/Y-124 sandwiches. This mechanism, inelastic electron scattering in intermixed nonmagnetic layers at the interface may induce strong repulsive interaction on the Cooper pair, may play a role for the minimum of $T_c$ at $d_1$. Furthermore, it is inferred that magnetic spin-flip scattering mechanism may play an important role in causing the maximum of $T_c$ at $d_1$. 

In the HTS/CMR structure, Y-124 has high critical temperature and short coherence length, while LCMO is metallic with not so large pair breaking effects due to its weak magnetism. The well-matched lattice between Y-124 and LCMO weakens the effects of roughness and strain. In addition, the oxygen diffusion between LCMO and Y-124 layers is negligible in our samples. It is speculated that some coupling between top and bottom layers, through the spacer layer, plays an important role. A possible type of long-range coupling is dipolar coupling due to the roughness of the interface. In the presence of topographical inhomogeneities the magnetostatic coupling arisen from surface magnetic dipoles created by roughness may originate a non-negligible coupling. The dipolar interaction, under particular circumstances, can also originate non-in-plane magnetizations. The roughness of samples is less than 5 nm, and the dipolar coupling may play a role in the oscillation with the spacer thickness. Another possible mechanism may be related to the spin fluctuations in Y-124 and LCMO layers. The sandwiches can be considered to be a layered structure with Mn-O and Cu-O conduction planes which are stacked apart from each other. Chahra et al. think that spin fluctuations may be a key to understand the phenomena in HTS/CMR system. In contrast, Holden et al. reported recently the long-range charge transfer from HTS layer into CMR layer for HTS/CMR superlattices from optical measurements, and concluded that spin diffusion (driven by the gradient in spin polarization between CMR and HTS layers) can not lead to long-range spin polarization of charge carriers deep inside HTS layers.

In a word, our results provide evidence for interplay of ferromagnetic and superconducting couplings in HTS/CMR layered systems. To date, we do not have a complete microscopic understanding of these features yet. Further studies are required before one can distinguish between these equally fascinating possibilities.

3 Conclusion

The interlayer coupling of superconducting Y-124 thin films through ferromagnetic LCMO layer was investigated from transport properties of Y-124/LCMO/Y-124 sandwiches. The strongest nonmonotonic information in $T_c$ at $d_1$ curves appears clearly at the region $d_1 > d_1^{\text{CR}}$. This kind of dependence on spacer layer suggests strongly the interplay of ferromagnetic and superconducting couplings in HTS/CMR layered systems.
References:


