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Superconducting Transition Temperature in $YBa_2Cu_4O_8/La_{2/3}Ca_{1/3}MnO_3/YBa_2Cu_4O_8$ Heterostructure

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Abstract: $YBa_2Cu_4O_8/La_{2/3}Ca_{1/3}MnO_3/YBa_2Cu_4O_8$ (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 $d_L{}^{CR}$. The metal-insulator transition temperature can only be detected at $d_L > d_L{}^{CR}$. The dependence on the spacer layer in LCMO/Y-124 systems suggests strongly the interplay of ferromagnetic and superconducting couplings.

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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'ko[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[7] suggested that the unusual effects predicated 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[11] reported the observation of supercurrents in trilayer junctions with a 500 nm thick $La_{0.7}Ca_{0.3}MnO_z$ ferromagnetic barrier. Recently, Holden et al[12] investigated ellipsometric measurements of far-infrared dielectric properties of $YBa_2Cu_3O_7/La_{2/3}Ca_{1/3}MnO_3$ 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 $YBa_2Cu_3O_7$ and $La_{2/3}Ca_{1/3}MnO_3$ films[12]. Pena et al[13] found experimental evidence for coupling between superconducting layers through ferromagnetic spacer in $YBa_2Cu_3O_7/La_{0.7}Ca_{0.3}MnO_3$ superlattices consistent with long-range F/S proximity effect.

In our previous work, we[14] found that the T_C of $YBa_2Cu_4O_8$ layer was strongly suppressed by ferromagnetic $La_{2/3}Ca_{1/3}MnO_3$ layers due to magnetic proximity effect in $La_{2/3}Ca_{1/3}MnO_3/YBa_2Cu_4O_8/La_{2/3}Ca_{1/3}MnO_3$ sandwiches. In this paper, a complex T_C oscillation phenomena for $YBa_2Cu_4O_8$ (Y-124)/$La_{2/3}Ca_{1/3}MnO_3$ (LCMO)/Y-124 heterostructure was reported. Here, Y-124 was chosed only because it is much more stable than $YBa_2Cu_3O_7$ in different oxygen environments.

1 Experimental

Heterostructure was fabricated on (001) $SrTiO_3$ (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 $nm \cdot s^{-1}$ for LCMO layer and 0.075 $nm \cdot s^{-1}$ 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 diamagnetic response.

2 Results and Discussion

Fig. 1 shows temperature dependence of relative resistivity ($\rho/\rho_{100\,K}$) and its temperature coefficient ($d(\rho/\rho_{100\,K})/dT$) 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 $A \cdot m^{-1}$, 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 $La_{0.67}Ca_{0.33}MnO_3$ 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

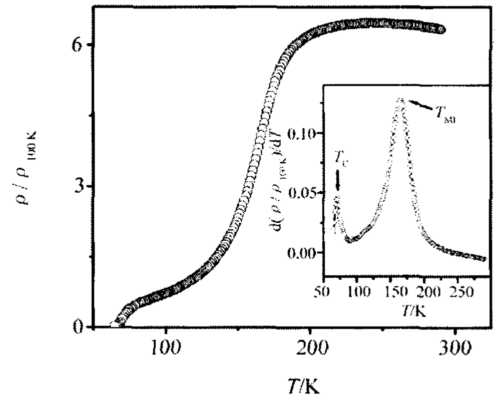

Fig. 1 Temperature dependence of resistivity ($\rho/\rho_{100\,K}$) and its temperature coefficient ($d(\rho/\rho_{100\,K})/dT$) of Y-124 (75 nm)/LCMO (75 nm)/Y-124 (75 nm) film (T_{MI} and T_C are defined as peak points in the differential curve as shown in the inset)

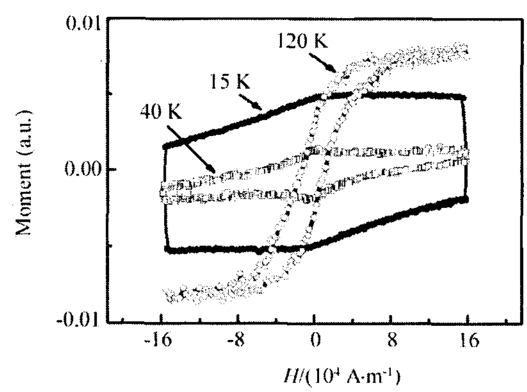

Fig. 2 Magnetic hysteresis loops of Y-124 (75 nm)/LCMO (75 nm)/Y-124 (75 nm) film with magnetic field parallel to film plane

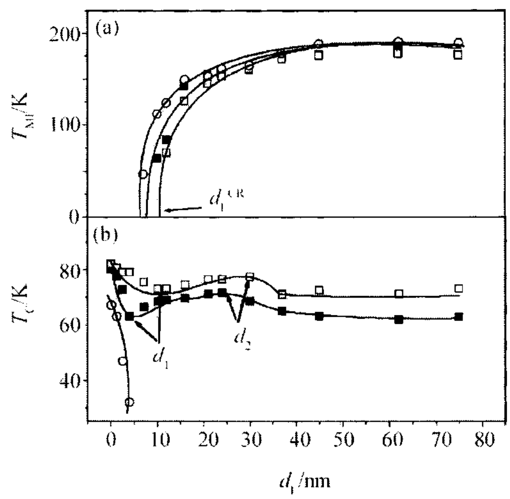

Fig.3 T_C and T_{MI} of (a) Y-124 (7.5 nm)/LCMO (d_L)/Y-124 (7.5 nm) (○), (b) Y-124 (45 nm)/LCMO (d_L)/Y-124 (45 nm) (■) and (c) Y-124 (75 nm)/LCMO (d_L)/Y-124 (75 nm) (□) versus d_L

drop of T_{MI} in LCMO film if $d_L < 40$ nm, and even without MR transition for $d_L \leqslant 3$ nm. In our case, the larger threshold value d_L^{CR} may be corresponding to the nonmagnetic (or magnetically 'dead') interfacial layer resulted from the roughness at the interface[22].

Fig.3 also shows the d_L dependence of T_C for Y-124/LCMO/Y-124 trilayer films. For $d_Y = 7.5$ nm, T_C exhibits a rapid drop with increasing d_L and is not detected when $d_L > 6$ nm in our setup. In the other two series, T_C exhibits a minimum with increasing d_L up to d_1 for ultra-thin LCMO layer. As d_L is further increased from d_1, T_C rises to a maximum at $d_2 \sim 30$ nm. T_C is essentially independent of d_L for $d_L >> 50$ nm and is ~65 and 70 K for $d_Y = 45$ and 75 nm when $d_L = 80$ nm. In a study of Fe/Nb system for different magnetic layer thickness, T_C reaches first minimum at d_{Fe} and ferromagnetism appears at almost the same Fe thickness as d_{Fe}[23,24]. In Gd/Nb system the first minimum of T_C also correlates with ferromagnetic ordering of Gd layer[25,26]. In contrast, it should be pointed out that T_{MI} is smaller than Curie temperature T_f for our thin samples with low T_f. So d_1 cannot be directly connected to the onset of ferromagnetism in LCMO layers. Although no evidence existed for nonmagnetic interfacial layers in 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[23,24]. Furthermore, it is inferred that magnetic spin-flip scattering mechanism may play an important role in causing the maximum of T_C at d_2[27].

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[14]. It is speculated that some coupling between top and bottom layers, through the spacer layer, plays an important role. A possible type of long-rang coupling is dipolar coupling due to the roughness of the interface[28~30]. In the presence of topographical inhomogeneities the magnetostatic coupling arisen from surface magnetic dipoles created by roughness may originate a non-negligible coupling[30]. 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. Chahara et al[31] think that spin fluctuations may be a key to understand the phenomena in HTS/CMR system. In contrast, Holden et al[12] 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 $T_C \sim d_L$ curves appears clearly at the region $d_L > d_L^{CR}$. This kind of dependence on spacer layer suggests strongly the interplay of ferromagnetic and superconducting couplings in HTS/CMR layered systems.

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