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Current enhanced magnetic proximity in $Nd_{0.7}Ca_{0.3}MnO_3/YBa_2Cu_3O_7$ bilayer

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The $Nd_{0.7}Ca_{0.3}MnO_3/YBa_2Cu_3O_7$ (NCMO/YBCO) bilayer is fabricated with the method of pulsed laser deposition, and the current dependent proximity effects are investigated. Our experimental data show that the suppression rate of superconducting transition temperature (T_c) with respect to the applied current (>1 mA) is enhanced by one order of magnitude in NCMO/YBCO compared with that in pure YBCO. The enhanced T_c suppression is attributed to pair breaking via the interactions with the spin-polarized quasiparticles and the magnetic exchange, in association with a current-induced melting of the charge-order state in NCMO. *© 2007 American Institute of Physics*.
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Transitional metal oxides with perovskite structures generated a great deal of interest since the 1950s due to their unusual electrical and magnetic properties. Two important findings in this context are the occurrence of high-temperature superconductivity (HTS) in copper oxide and of colossal magnetoresistance (CMR) in manganites. The proximity effect of HTS and CMR involves the intermixing and hybridization of the electronic structure near the interface, which results in a competition between two different long range orderings. The studies on the suppression of superconductivity by magnetic order in the heterostructures of CMR/HTS provide valuable information to understand the mechanism of HTS (Refs. 1–13) and lead to the design of new spin-injection devices. In the concept of spin-injection design, the spin-polarized quasiparticles flow from the ferromagnetic layer to the HTS layer without substantial spin flipping and thus destroy the superconducting pairs by breaking the time-reversal symmetry of the Cooper pairs.[14,15] However, most attention has been paid to the individual effect of either proximity or spin-polarized quasiparticles on the superconductivity. In this work, we fabricate the $Nd_{0.7}Ca_{0.3}MnO_3/YBa_2Cu_3O_7$ (NCMO/YBCO) bilayer and measure its current dependent transport properties in order to study the interplay of proximity and spin-polarized quasiparticles. According to previous reports, the polarization of $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) is around 80%;[16] thus, the diffusion length of the superconducting pairs of YBCO is relatively short (<30 nm) in LSMO. Therefore, we replace the ferromagnetic LSMO by a canted antiferromagnetic NCMO to study the interaction between superconductivity and magnetism. Regarding NCMO as a weak magnet at low temperature, the length scale of the superconducting proximity is expected to be much longer than that in LSMO.

The NCMO/YBCO bilayer was deposited on a $LaAlO_3$ (001) single crystal substrate by a commercial pulsed laser deposition system (Neocera Pioneer 180) with a KrF (248 nm) laser. During the deposition, the substrate temperature was kept at 850 and 780 °C in the flowing O_2 atmosphere of 50 mTorr for YBCO and NCMO layers, respectively. It was followed by O_2 annealing at 400 °C for 60 min under an oxygen pressure of 300 Torr. The thicknesses of the YBCO and NCMO layers were 160 and 40 nm, respectively. Pure NCMO and YBCO films were also made and characterized for the purpose of comparison. X-ray diffraction and scanning electron microscopy were utilized to determine the phase purity of the sample. Both NCMO and YBCO were found to be high quality epitaxial layers with the *c* axis perpendicular to the film surface. On top of NCMO, Au leads were attached to the surface using indium pads. Temperature dependent resistivity measurements were carried out with a standard four-probe configuration in a closed-cycle low-temperature system. Keithley 220 and 182 were used as the current source and the voltage meter, respectively. Temperature dependent magnetizations were measured by a superconducting quantum interference device system (Quantum Design) at a field of 100 Oe.

The image of high resolution transmission electron microscopy (HRTEM) was taken at the interface of NCMO/YBCO, along with a profile of energy dispersive spectroscopy (EDS) across the interface. Based on the elemental analysis, there is no significant chemical diffusion at the interface. The Data of HRTEM and of chemical analysis have been added as Figs. 1(a) and 1(b), respectively.

Figure 2 is the plot of magnetization (M) vs temperature (T) for a NCMO/YBCO bilayer. The M-T curves for YBCO

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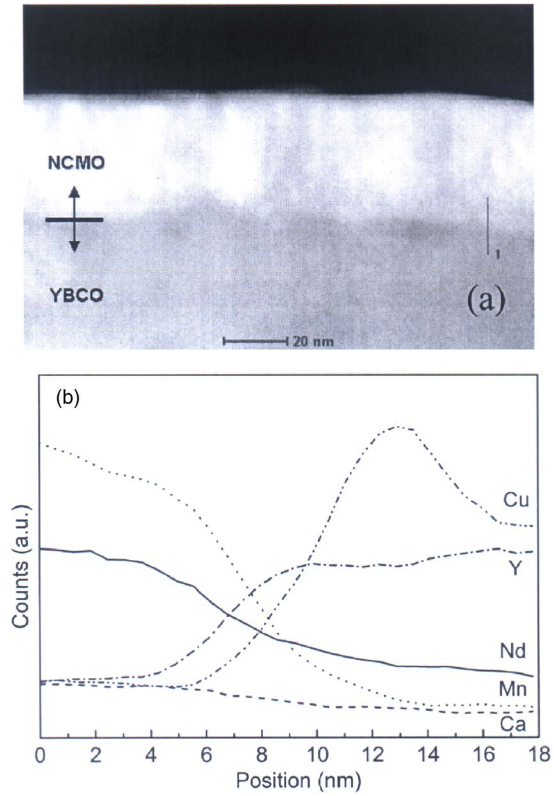

FIG. 1. (Color online) (a) Image of HRTEM at the interface of NCMO/YBCO; (b) profile of EDS across the interface. The vertical line indicates the path of scanning within 18 nm.

and NCMO are also plotted in the lower right inset and the upper right inset, respectively. Based on the M-T curves, the superconducting transition temperature (T_c) and the canted antiferromagnetic transition temperature (T_N) are determined as T_c=88 K for a single YBCO layer, T_N=100 K for a single NCMO layer, and T_N=100 K and T_c=82 K for a NCMO/YBCO bilayer. The results in Fig. 2 indicate that under the proximity effect, T_N retains the same value while T_c is suppressed from 88 to 82 K.

Figure 3 plots the T-dependent resistivity (ρ) of YBCO with the applied current I_a varying from 0.1 to 90 mA. It

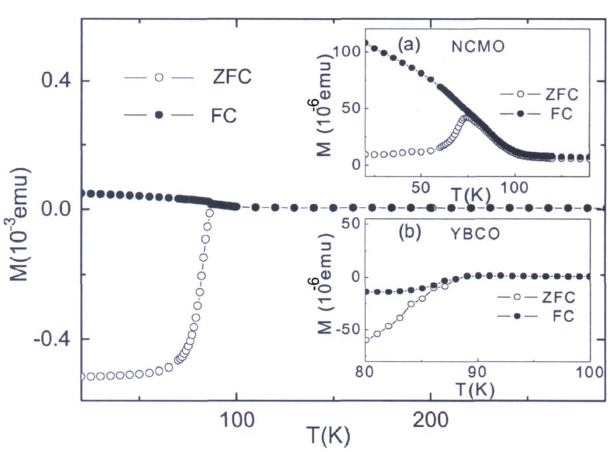

FIG. 2. (Color online) Magnetization (M) vs temperature (T) for a NCMO/YBCO bilayer. The M-T curves for a single YBCO layer and a single NCMO layer are also plotted in the lower right inset and the upper right inset, respectively. Open circles represent the zero-field data, and close circles are data with the field-cooled mode.

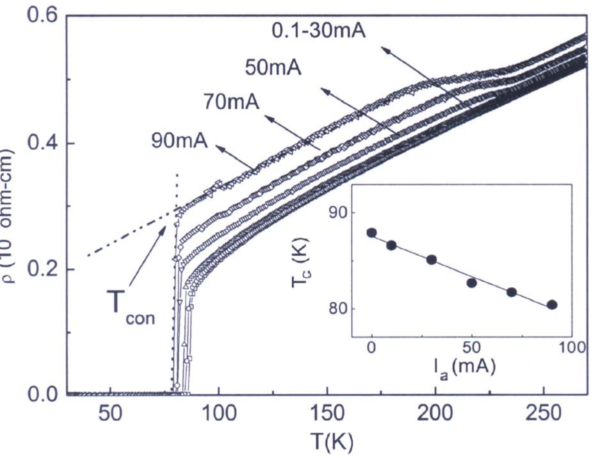

FIG. 3. (Color online) Temperature dependent resistivity $\rho(T)$ curve for the single YBCO layer with applied current varying from 0.1 to 90 mA. The onset of the transition temperature is defined as the crossing point of an extended line from the precipitous slope of transition (see the dotted line) and an extracted line of the normal state (see the dash-dotted line). The inset plots the onset transition temperature vs applied current I_a.

shows that the superconducting transition occurs at an onset temperature T_{con} around 87.9 K and ρ becomes zero around 86.1 K. The onset of the transition temperature is defined as the crossing point of an extended line from the precipitous slope of transition (see the dotted line) and an extracted line of the normal state (see the dash-dotted line). The onset temperature is consistent with the value of T_c obtained from the M-T measurement. Therefore, T_{con} is regarded as T_c in the following context. According to Fig. 3, $\rho(T)$ is not affected by changing the current within the current range of 0.1–1 mA, while at higher current its normal state starts increasing with a T_c reduction, indicating the existence of a threshold current for generating the nonequilibrium quasiparticles. An abrupt increase of the normal state ρ appears at around 220 K, which becomes more pronounced at higher I_a. The origin of this abnormal ρ increase is not understood yet, but the systematic increase of the normal state ρ with increasing current can be related to the scattering process of quasiparticles. Based on the slope of T_c vs I_a (see the inset in Fig. 3), the T_c supression rate by the ordinary quasiparticle is 0.1 K/mA.

Figure 4 displays the current dependent $\rho(T)$ for a NCMO film with I_a=0.0001–1 mA. Within this range of current, data are all overlapped into one curve. The deviation from the curve represents the cutoff of resistivity at various currents due to the voltage limit of instrument. Although all measured $\rho(T)$ curves for NCMO show an insulating behavior through I_a=0.0001–50 mA, the absolute value of $\rho(T)$ is actually reduced at high current, as shown in the inset in Fig. 3 for I_a=5–30 mA. The current-induced reduction of resistivity was observed previously in bulk $Nd_{0.5}Ca_{0.5}MnO_3$ and $Pr_{0.7}Ca_{0.3}MnO_3$,[17–21] and it was interpreted as the melting of the charge-order state.

Figure 5 shows the $\rho(T)$ of the NCMO/YBCO bilayer with I_a=0.001–40 mA. The $\rho(T)$ curves for I_a=0.001, 0.01, 0.1, and 1 mA all coincide as one curve, suggesting that the resistivity is not varied by the current within this current range. Based on this curve, the value of ρ at room temperature is two orders lower than that of NCMO, and the slope of $\rho(T)$ changes its sign from negative to positive at around

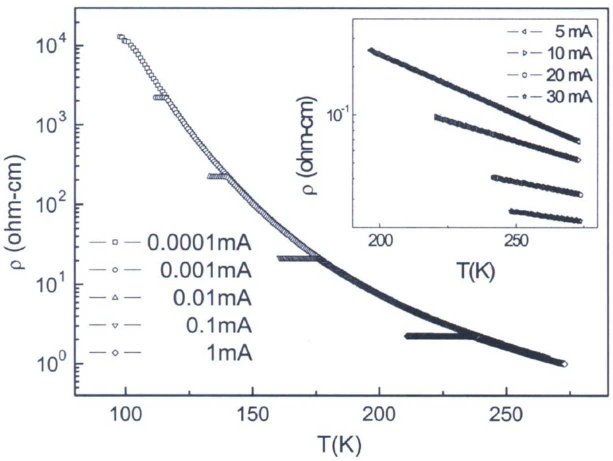

FIG. 4. (Color online) Temperature dependent resistivity $\rho(T)$ curve for the single NCMO layer with applied current varying from 0.0001 to 1 mA. The inset shows the $\rho(T)$ curve with applied current from 5 to 30 mA in a log scale.

160 K. This result indicates that the normal state property of NCMO/YBCO is completely different from either YBCO or NCMO. The characteristic of $\rho(T)$ of the NCMO/YBCO bilayer reflects the proximity effect of YBCO on NCMO and is consistent with the previous report on the $YBCO/Pr_{0.67}Ca_{0.33}MnO_3$ bilayer.[22] The superconductivity of NCMO/YBCO occurs at 82 K, which is only 6 K lower than that of YBCO. It is thus evident that the diffusion length of the superconducting pair is much longer than 40 nm in NCMO. With increasing I_a from 1 to 40 mA, the value of $\rho(300\text{ K})$ is reduced by 40% and T_c is suppressed down to 34 K. A simple estimation of current-induced T_c suppression yields an average value of 1.2 K/mA, which is one order larger than that in YBCO and thus cannot be simply attributed to the injection of ordinary quasiparticles. Furthermore, unlike in the case of YBCO, the normal state $\rho(T)$ is reduced by the current in the NCMO/YBCO bilayer. The significant reduction of $\rho(300\text{ K})$ suggests that the number of carriers is increased under the application of high current. It is consistent with the picture that in the NCMO system when the charge ordering is broken down by a high current, the double-exchange conductance increases, leading to the transition from an antiferromagnetic to a ferromagnetic state as well as from an insulating to a metallic state. Consequently, this transition leads to the enhancement of exchange field in NCMO, which in turn polarizes the injected quasiparticles.

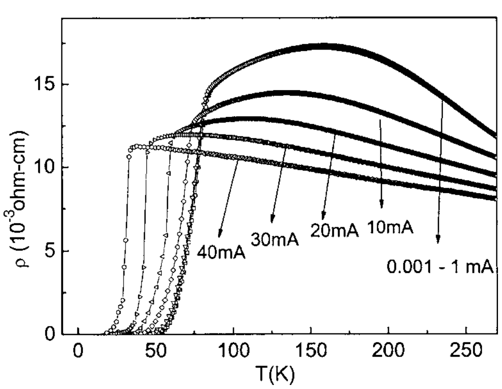

FIG. 5. Temperature dependent resistivity $\rho(T)$ curve for the NCMO/YBCO bilayer with applied current from 0.001 to 40 mA.

Both spin-polarized quasiparticles and exchange field could diminish superconductivity by breaking the Cooper pairs. It explains why the current-induced T_c suppression in NCMO/YBCO is much severe compared with that in YBCO.

In conclusion, the NCMO (40 nm)/YBCO (160 nm) bilayer is fabricated, and its temperature dependent electrical properties with varying applied currents are investigated. It is found that the suppression rate of the superconducting transition temperature of NCMO/YBCO with respect to current (>1 mA) is one order higher than that in pure YBCO. Meanwhile, its normal state resistivity is reduced by over 40% of its pristine value at $I_a=40$ mA. Since the great reduction of the normal state resistivity is likely related to the current-induced melting of the charge-order state in NCMO, the large T_c suppression in NCMO/YBCO shall be attributed to the generation of spin-polarized quasiparticles and the enhancement of exchange field due to the presence of ferromagnetic phase.

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