Effect of superconductivity on the electronic transport and capacitance of $La_{1.85}Sr_{0.15}CuO_4$/Nb doped $SrTiO_3$ heterojunction

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The authors report the effect of superconductivity on the electronic transport and capacitance of $La_{1.85}Sr_{0.15}CuO_4$/Nb doped $SrTiO_3$ heterojunction. This heterojunction shows good rectifying property. With the occurrence of superconductivity, the capacitance, junction resistance, and diffusion voltage of the heterojunction show jumps, which correlate with the resistance change of $La_{1.85}Sr_{0.15}CuO_4$. Analysis shows that the current-voltage behavior of the heterojunction is consistent with that of the inhomogeneous Schottky contacts. The results were discussed by considering the effect of superconductivity on the inhomogeneous heterojunction. This work is helpful for the understanding of superconductor based heterojunctions and inhomogeneous Schottky contacts. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2904628]

Perovskite oxides show various interesting properties, such as colossal magnetoresistance, superconductivity, ferroelectricity, etc. This diversity provides a good opportunity for studying the effect of various properties on the behavior of the heterojunctions and the resultant functionality and tunability. In this regard, heterojunctions based on high temperature superconductors (HTSs) are interesting considering the interesting properties of HTS. The central topic of this study is the effect of superconductivity on the characteristics of the heterojunctions. There have been some reports on heterojunctions composed of HTS and the Nb doped $SrTiO_3$.[1–6] These heterojunctions show the diodelike behavior. However, it is not clear whether superconductivity can affect the characteristics of the heterojunctions. There are some reports about the absence of the effect of superconductivity on the characteristics of the heterojunctions.[1,5] On the other hand, there are also some reports on a visible reduction in the diffusion voltage of the junction with the occurrence of superconducting transition deduced from the current-voltage (*I-V*) curves.[3,6] However, the *I-V* curves in these work were obtained by the four-probe method, which is not as reliable as that of the commonly used two-probe method, especially for films with large resistance.[7] For the four-probe method, the current and voltage electrodes are not at the same site of the film, so there is a potential difference between them and this potential difference changes with temperature due to the change of the film resistance with temperature. Since the reported change of diffusion voltage around the superconducting transition temperature (T_c) is minor[3,6] and may be easily affected by the measurement approach, it is needful to carry out the measurement with the two-probe method. Moreover, it has been shown that the diffusion voltage obtained from the capacitance-voltage (*C-V*) curves is more accurate than that obtained from the *I-V* curves.[8] Actually, the study on the capacitance of HTS based heterojunctions is rather limited,[2] although capacitance is very useful for their study, and there are no reports on the effect of superconductivity on the capacitance of the heterojunctions composed of HTS and the Nb doped $SrTiO_3$. In this letter, we investigated the electronic transport and capacitance properties of heterojunction composed of $La_{1.85}Sr_{0.15}CuO_4$ (LSCO) and Nb doped $SrTiO_3$. It was found that superconductivity affects the characteristics of the heterojunction.

LSCO films were grown on (001) oriented 0.7 wt % Nb doped $SrTiO_3$ (NSTO) single crystal substrates by pulsed laser deposition to get the heterojunctions. LSCO films were also grown on $SrTiO_3$ (STO) substrates with the same conditions. X-ray diffraction data indicate that LSCO film is (001) oriented. The temperature dependence of resistance for LSCO film grown on STO was measured by using the four-probe method. Au was deposited on both LSCO and the back of NSTO as electrodes. Both Au/LSCO and Au/NSTO are

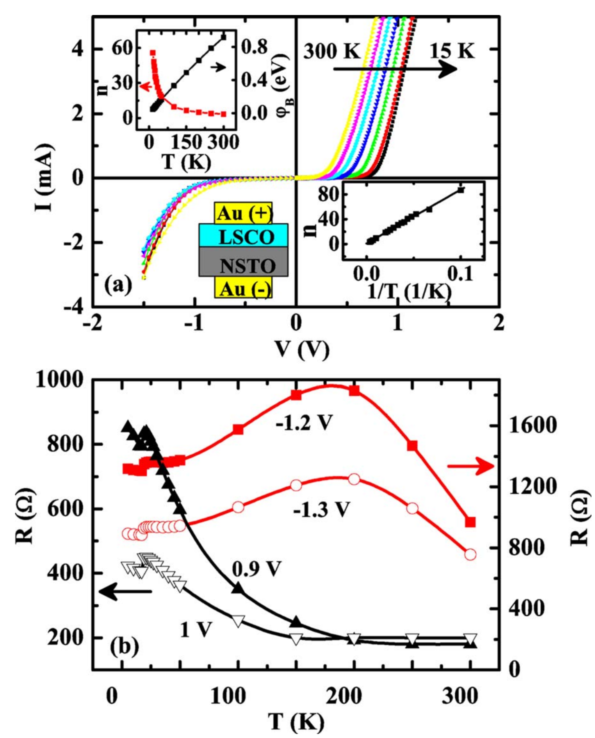

FIG. 1. (Color online) (a) *I-V* curves of LSCO/NSTO at different temperatures (300, 250, 200, 150, 100, 50, and 15 K). The top inset shows *n-T* and ϕ_B-*T* obtained from the *I-V* curves. The left bottom inset is the layout of the device for measurement. The right bottom inset is the *n*-1/*T* curve. (b) R_j-*T* curves with different bias voltages.

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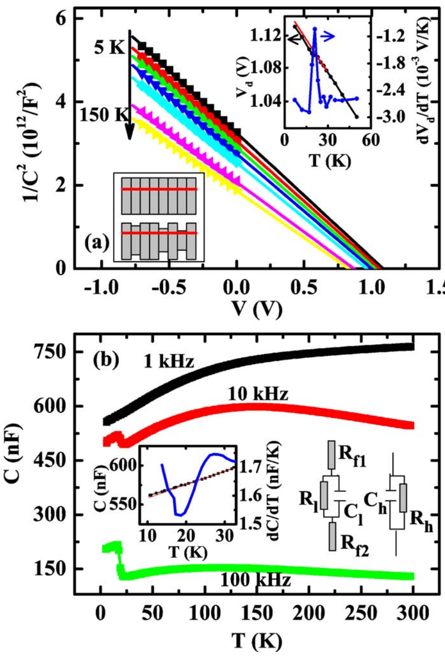

FIG. 2. (Color online) (a) $1/C^2$-V curves at different temperatures (150, 100, 50, 35, 25, 15, and 5 K). The top inset shows V_d-T derived from $1/C^2$-V and dV_d/dT-T curves. The bottom inset shows illustration of depletion layer of homogeneity (top) and inhomogeneity (bottom); the red line represents the interface. (b) C-T curves of LSCO/NSTO under different frequencies. The left inset shows C-T and dC/dT-T under 1 kHz. The right inset shows equivalent circuit units.

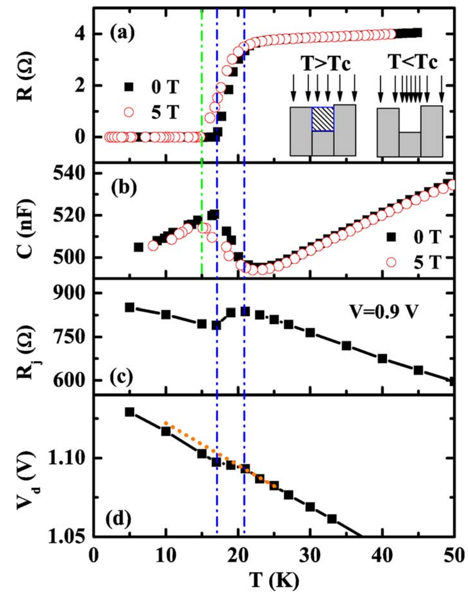

FIG. 3. (Color online) (a) R-T curves of LSCO film without and with a 5 T magnetic field. The inset is a schematic illustration showing the current distribution change before and after superconducting transition. The arrows represent current, and the rectangles with different heights represent the local depletion layers with different thicknesses. The shaded region represents the filament, which blocks the current. (b) C-T curves of LSCO/NSTO junction without and with a 5 T magnetic field. (c) R_j-T curve of LSCO/NSTO junction. (d) V_d-T curve of LSCO/NSTO.

Ohmic contacts. The layout of the device is shown in the left bottom inset of Fig. 1(a). I-V curves were measured by the two-probe method by using a Keithley 2400 source meter. C-V curves were measured by a ZM2353 *LCR* meter with measuring frequency of 1 kHz and the capacitance-temperature (C-T) curves were measured at different frequencies.

Figure 1(a) shows the I-V curves of the LSCO/NSTO heterojunction at different temperatures and they show good rectifying property. With decreasing temperature, the forward biased curves shift to higher voltages. Generally, heterojunctions composed of HTS and NSTO were regarded as the Schottky contacts.[2,5] According to the conventional thermionic emission theory, the forward current can be described by the following equation:[9]

$$I = AA^* T^2 \exp(-q\phi_B/kT)\exp(qV/nkT)\{1-\exp(-qV/kT)\}, \quad (1)$$

where A, A^*, q, and k are the sample area, the Richardson constant, the electronic charge, and the Boltzmann constant, respectively. ϕ_B and n are the Schottky barrier height and ideality factor, respectively. The I-V curves of LSCO/NSTO can be fitted by Eq. (1) and the parameters ϕ_B and n are shown in the top inset of Fig. 1(a). Here, ϕ_B linearly decreases with decreasing temperature. The value of n is 3.4 at room temperature, larger than unity, and increases with decreasing temperature satisfying $n=1+T_0/T$.[10] These characteristics are much different from those of the ideal Schottky contact.[9] In order to further analyze the transport property of the junction, the junction resistance (defined by $R_j=V/I$) was calculated and the temperature dependences of R_j under different bias voltages are displayed in Fig. 1(b). A jump of R_j can be seen at T_c. Since the out-of-plane resistance of LSCO film is much smaller than the magnitude of the jump, this jump should come from the junction.

Figure 2(a) is the $1/C^2$-V curves of LSCO/NSTO at different temperatures with low reverse bias voltages and they exhibit a linear behavior, which is expected for the Schottky contacts. According to the theory of Schottky contacts, $1/C^2$-V of LSCO/NSTO is described by the following relation:[9]

$$\frac{1}{C^2} = \frac{2}{A^2}\frac{V_d - V}{q\varepsilon_0\varepsilon_{\mathrm{NSTO}}N_{\mathrm{NSTO}}}, \quad (2)$$

where C is the capacitance, A is the effective area of the junction, V_d is the diffusion potential at zero bias, $\varepsilon_{\mathrm{NSTO}}$ is the permittivity of NSTO, and N_{NSTO} is the carrier density of NSTO. The top inset of Fig. 2(a) is the temperature dependence of V_d obtained from Fig. 2(a) according to Eq. (2). At T_c, V_d shows a deviation from the smooth increase with decreasing temperature and this change is more remarkable in the dV_d/dT curve. Figure 2(b) is the temperature dependence of capacitances of LSCO/NSTO at different frequencies. An increase in capacitance occurs at T_c and the magnitude of this jump increases with increasing frequency. At 1 kHz, only a small jump can be seen, as shown in the left inset of Fig. 2(b).

Figure 3 shows the changes at T_c of LSCO resistance, capacitance, junction resistance, and the diffusion voltage. It can be seen that they are correlated. The effect of magnetic field on C-T and R-T was also studied. As seen from Figs. 3(a) and 3(b), both the superconducting transition and jumps of C-T broaden upon applying a 5 T magnetic field. These correlations suggest that the resistance change of LSCO upon superconducting transition plays an important role in the changes of characteristics of LSCO/NSTO. For the visible reduction in V_d deduced from the current-voltage curves with the occurrence of superconducting transition,[6] it has been proposed that it is related to the superconducting gap[6] by using the schematic illustration of the energy levels of the

HTS based heterojunctions,[4] in that they set the Fermi level of NSTO in the band gap.[4] However, it is well established that NSTO is a degenerated semiconductor and its Fermi level is above the bottom of conducting band.[8,11] Besides, Xiang *et al.* found that ΔV_d of their LSCO/NSTO heterojunction begins to decrease below 10 K, which is different from the expected temperature dependence of the superconducting gap.[6] Here, we propose an alternative scenario based on the inhomogeneity of heterojunction to account for the effect of superconductivity on capacitance, R_j and V_d of LSCO/NSTO. Inhomogeneity has been well established for semiconductor based Schottky contacts,[12] in which ϕ_B and n derived from *I-V* curves are temperature sensitive.[13] Recently, Ramadan *et al.* reported inhomogenous behavior of $YBa_2Cu_3O_{7-\delta}$/NSTO heterojunction, which shows a linear decrease in ϕ_B with T, larger value of n, although the high quality of the heterojunction was ensured by the scanning transmission electron microscopy.[5] As shown in the top inset of Fig. 1(a), ϕ_B of LSCO/NSTO linearly decreases with decreasing temperature, while n is larger than 1 and increases with decreasing temperature. These behaviors are consistent with the Schottky contacts with inhomogeneity. The presence of inhomogeneity in LSCO/NSTO can be understood considering the reports of inhomogeneous surface of $SrTiO_3$ (Ref. 14) and Nb stripes on the surface of NSTO.[15] Thus, LSCO/NSTO heterojunction is expected to be inhomogeneous and the barrier height varies at different places of the interface. According to the theory of heterojunctions,[9] the thickness of the depletion layers at the interface is proportional to $V_d^{1/2}$, and V_d equals the barrier height minus a constant. So the depletion layer is thin at the place where the barrier height is low. A few thin filaments can form in the low barrier region adjacent in regions with high barriers on both sides of the interface, as shown in the bottom inset of Fig. 2(a). The resistances of these filaments are large above T_c because of their thin diameters.[5] When LSCO becomes superconducting at T_c, the resistances of the filaments through the low barrier regions will show an abrupt decrease because of the occurrence of superconductivity in LSCO. This leads to a redistribution of current through the interface and more carriers flow via low barrier regions, as shown in the inset of Fig. 3(a). Thus, low barrier regions will have more contribution to the mean barrier height, resulting in the decrease in the barrier height of the heterojunction. This can account for the change of V_d at T_c. The decrease in junction resistance at T_c can also be understood because the low barrier regions have more contribution upon superconducting transition. From Eq. (2), we get a differential equation $\Delta V_d = -(A^2 q \varepsilon_0 \varepsilon_{\mathrm{NSTO}} N_{\mathrm{NSTO}}/C^3)\Delta C$, which can account for the capacitance increase at T_c.

By imitating to transistor,[16] the heterojunction can be regarded as parallel of many units considering that resistance of LSCO is small. Typical units are shown in the right inset of Fig. 2(b). The left corresponds to the local region with low barrier height, adding the filaments. The right corresponds to the local region with high barrier height. The equivalent capacitances satisfy $C_{\mathrm{low}} = [1+(1/\omega^2 C_l^2 R_l^2)]/\{[1+(1/\omega^2 C_l^2 R_l^2)] + \omega^2 C_l^2 (R_{f1}+R_{f2})^2\} C_l$ and $C_{\mathrm{high}} = C_h$, respectively, where R_{f1}/R_{f2} are resistances of the filaments on LSCO/NSTO sides, C_l/C_h are barrier capacitances at local region with low/high barrier heights, respectively, R_l is the barrier resistance at local region with low barrier height, and $C_{\mathrm{low}}/C_{\mathrm{high}}$ are equivalent capacitances at local region with low/high barrier heights. The total capacitance is the sum of all units. As seen from the formula of C_{low}, it decreases and deviates from the barrier capacitance with increasing frequency, which is consistent with the experimental results. The jump becomes larger with increasing frequency, which can be obtained from the above equivalent capacitance equations. This equivalent circuit model has also been used to account for the frequency dependence of the capacitance jump in $BaTiO_3/YBa_2Cu_3O_7$ heterojunction.[17]

In conclusion, jumps of R_j, capacitance, and V_d, which are related to superconducting transition, were observed in LSCO/NSTO heterojunction. These jumps can be understood by considering the inhomogeneity of the heterojunction. This work demonstrates that heterojunction based on HTS can show interesting properties and may shed light on the understanding of the characteristics of superconductor based heterojunctions.

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