Rectifying properties of the $YBa_2Cu_3O_{7-\delta}/SrTiO_3$:Nb heterojunction

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A heterojunction has been fabricated by growing a $YBa_2Cu_3O_{7-\delta}$ (YBCO) film of the thickness of 1000 Å on a 0.5 wt %Nb-doped SrTiO3 (STON) crystal, and its resistive behavior was experimentally studied. The strong asymmetry of the current-voltage ($I-V$) relation with respect to bias polarity indicates an excellent rectifying property of the junction in the whole temperature range studied. The superconducting transition of YBCO causes a visible reduction of diffusion potential, measured by the forward voltage corresponding to the current rush in the $I-V$ curves, though the general rectifying behavior remains unchanged. This is possibly a result of the variation of the Fermi level of YBCO relative to that of STON, and suggests an alternative technique detecting the effects of superconducting transition in YBCO. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2136407]

There were several attempts to construct heterojunctions using manganites and La/Nb-doped $SrTiO_3$. Sandwiching a $SrTiO_3$ layer between a $La_{0.9}Sr_{0.1}MnO_3$ and a $La_{0.05}Sr_{0.95}TiO_3$ layers, Sugiura and collaborators fabricated the first manganite *p-n* junction that shows an excellent rectifying property in a wide temperature range.[1] Kawai further demonstrated that the intermediate layer was unnecessary, and constructed a heterojunction displaying all the main features of a *p-n* junction simply using $La_{0.9}Ba_{0.1}MnO_3$ and 0.01 wt %Nb-doped $SrTiO_3$.[2] A recent study further revealed the magnetically tunable character of the manganite-based junction: The diffusion/breakdown voltage and junction resistance undergo a great change under external magnetic field.[3] As is well-known, for properly hole-doped manganites the metal-to-insulator transition, thus the band structure of the manganite, can easily be modified by magnetic field. In contrast, the electronic structure of $SrTiO_3$ varies smoothly with temperature and is relatively insensitive to magnetic field.[4] This actually implies a field-induced variation of the interfacial potential produced by the interlayer diffusion of holes and electrons between manganites and $SrTiO_3$.

Based on the above discussion, it is clear that $SrTiO_3$ can be used as a reference for the measurement of relative change of another polar of the *p-n* junction. This is a convenient approach and sometimes may provide valuable information unavailable for ordinary techniques. Indeed, in the previous work on manganite heterojunctions a significant enhancement of diffusion potential was observed below the ferromagnetic transition of the manganite, which has been ascribed to the splitting of the conduction and valence bands of the manganite with respect to that of $SrTiO_3$.[3] We noticed that most of the previous work was on the manganite heterojunctions. In fact, the behavior of the *p-n* junction composed of other perovskite oxides that experience a complex process is also an interesting issue. As is well known, the properly hole-doped cuprate $YBa_2Cu_3O_{7-\delta}$ (YBCO), which has a structure related to $SrTiO_3$, exhibits a great change in resistivity at the superconducting transition, and a band gap of 30–60 meV near the Fermi level appears. It is also possible for the Fermi surface to undergo a visible distortion due to different band gaps in different directions. It is obviously interesting to ask what behaviors can be resulted by superconducting transition for YBCO heterojunctions.

A YBCO heterojunction was fabricated by growing a YBCO layer on a 0.5 wt %Nb-doped $SrTiO_3$ (STON) substrate of (001) orientation by magnetron sputtering. To obtain a better interface structure, the substrate was carefully polished and the surface roughness was depressed below 4 Å. The temperature of the substrate was kept at 800 °C and the oxygen partial pressure at ~400 mbar during the deposition. The film is 3×5 mm^2 in area and ~100 nm in thickness.

X-ray diffraction study confirmed that the film is single-phase and epitaxially grown with the (001) axis aligning along the film normal. Figure 1 shows the temperature-dependent resistance of YBCO measured along film plane. It reveals a superconducting transition at $T_C\approx90$ K, characterized by a resistance drop from ~3.8 Ω to ~0.

The current-voltage ($I-V$) curves of YBCO/STON were measured by the four-point method with two electrodes on YBCO (electrode separation ~1 mm) and the other two on

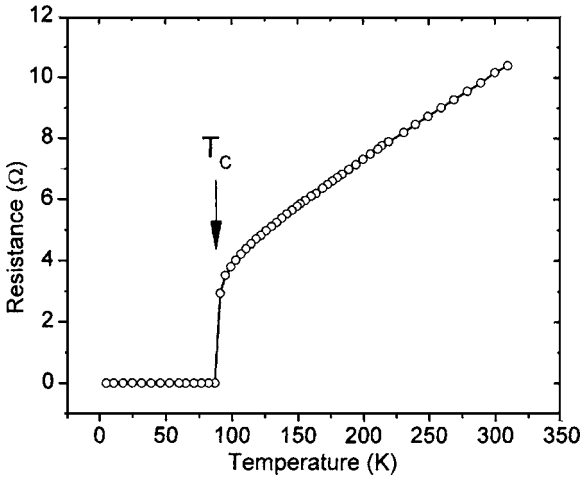

FIG. 1. Resistivity of YBCO as a function of temperature measured along film plane. Arrow marks the superconducting transition.

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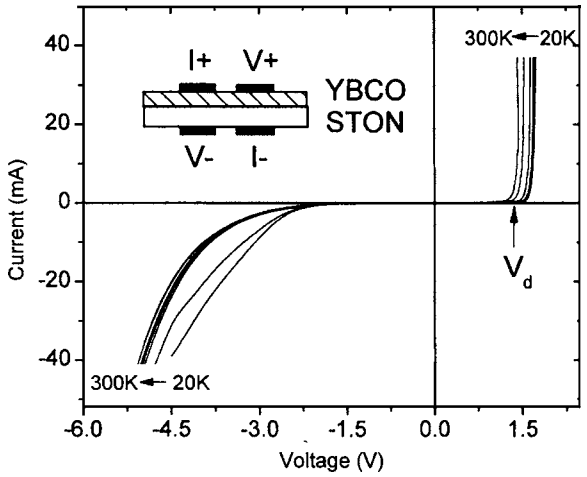

FIG. 2. Current-voltage characteristics of YBCO/STON measured at selected temperatures below 300 K by tuning bias voltage. Electrode setting for the measurement is schematically shown in the inset.

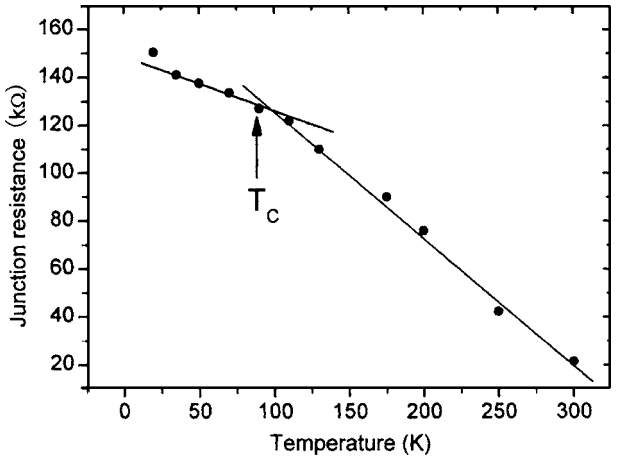

FIG. 3. Zero-bias junction resistance as a function of temperature. Solid lines are guides for the eye.

STON. The area of the silver electrode pad is ~1 mm^2. Figure 2 presents the $I-V$ curves of YBCO/STON recorded at different temperatures below 300 K. The $I-V$ relation is strongly asymmetric with respect to bias polarity. The current exhibits an abrupt jump at V_d for the forward bias while a gradual increase far beyond $|V_d|$ in opposite direction. The current is rather small in the low bias range, indicating fairly large junction resistance.

According to the standard semiconductor theory, V_d could be a measure of the diffusion potential near the YBCO/STON interface, which arises from the mutual diffusion of holes and electrons between YBCO and STON. The gradual growth of current for the backward bias could be a sign of electric breakdown. It is interesting that the diffusion voltage in YBCO/STON is ~4 times as large as that in manganite heterojunctions. This could be a result of the fact that the band gap in YBCO is much wider than that in manganite. In YBCO the energy gap between the conduction band and valence band is ~6 eV. In contrast, the energy gap between the spin-up and spin-down e_g bands in the manganite is ~1.5 eV.[5] For a *p-n* junction, it is obvious that the larger the band gap of one polar is, generally the greater the diffusion potential will be if the second polar is fixed.

The meaning of this result is twofold. The first one is that it reveals the easy accessibility of oxide *p-n* junctions. Oxide *p-n* junction can be obtained by grouping a wide variety of oxides with different carriers, not limited to manganites. The second one is that the one-electron band structure predicts the behavior of the system fairly well despite the suspicions on its validity for strong electron correlated systems.

It is interesting that no obvious change in the general $I-V$ relations was observed around T_C despite the great resistance change of YBCO. This seems consistent with the fact that the band structure of YBCO remains essentially unchanged at the superconducting transition except for the opening up of a minor band gap of ~60 meV due to the formation of Cooper pairs noting the fact that the behavior of a *p-n* junction is mainly determined by interfacial potential, which is exclusively related to the band structures of the two polars when carrier type/density is fixed. However, resistive transition can still be identified from the variation of junction resistance, defined by $R_j = dV/dI$ for $I \to 0$. According to Fig. 3, R_j shows a rapid increase with T above T_C, and the superconducting transition causes a declining of the R_j-T slope from 537 to 262 Ω/K, yielding a visible inflection. This result actually implies a variation of diffusion potential when YBCO enters into the superconducting state. Figure 4 exemplifies the temperature-dependent diffusion voltage, defined by the forward voltage corresponding to the current rush in the $I-V$ curves. V_d shows a smooth growth with the decrease of temperature until a local maximum is reached at ~90 K, below which a detectable deviation from the original V_d-T track appears for further cooling, and the maximum deviation is tens mV. This cannot be a spurious behavior due to the four-point geometry of the measurement. It is obvious that YBCO is an equal-potential layer in the superconducting state. As reported before, STON exhibits a metallic conduction, and its resistance can be approximated by $R \propto T^2$ quite well below 160 K.[2,6] The resistance between the two electrodes with separation of ~1 mm is smaller than 0.0085 Ω below 120 K. This implies that the voltage difference between these two electrodes is at most ~0.3 mV considering the fact that the maximum current is 30 mA. Therefore, the complex variation of V_d shown in Fig. 4 is an intrinsic behavior. It may be an effect of superconducting transition of the YBCO layer on interfacial potential. Differences between the observed and the expected diffusion voltage, the latter is obtained by extrapolating the high temperature data to low

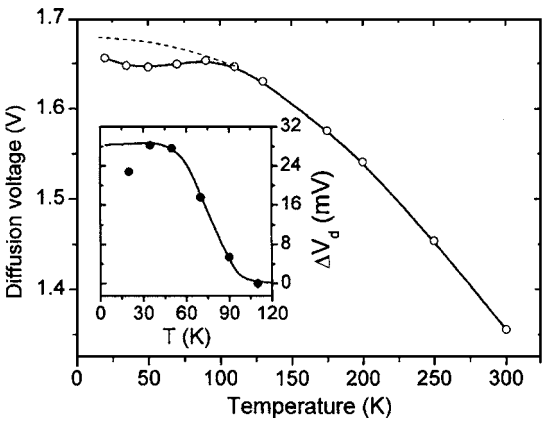

FIG. 4. Temperature-dependent diffusion voltage of YBCO/STON. Inset plot shows the differences between the observed (symbols) and the expected (dashed curve) diffusion voltages. Solid lines are guides for the eye.

temperatures by polynomial fitting, $V_d = 1.68 + 5.88 \times 10^{-5} T - 3.80 \times 10^{-6} T^2$, are calculated and the results are shown in the inset of Fig. 4. It demonstrates that the deviation appears at ~100 K, and develops with the decrease of temperature. A maximum, ~28 mV, is reached at ~40 K. It is interesting to note that the V_d anomaly appears at the very temperature for the superconducting onset, and the maximum deviation is the size of the band gap. *The sample was further annealed at* 700 °C *for* 20 min *in air then rapidly cooled to room temperature*. Subsequent measurement shows that with the disappearance of superconductivity of YBCO, the V_d anomalies disappeared accordingly (not shown). All these results strongly suggest a correlation of these behaviors with the superconducting transition of YBCO.

It is has been well established that the superconducting transition leads to a band gap of ~60 meV around the Fermi level of YBCO associated with the formation of Cooper pairs. The band gap may be different along different directions due to the asymmetry of the crystal structure of YBCO. This actually imply a possible distortion of Fermi surface, therefore, a variation of Fermi level taking into account the fact that the reciprocal volume surrounded by Fermi surface will keep constant through the superconducting transition. It is possible that the variation of Fermi level will affect the diffusion potential at the YBCO/STON interface, and the decrease of V_d suggests a growth of the Fermi level of YBCO with respect to that of STON, i.e., the establishment of superconducting band gap pushes upwards the Fermi level of YBCO slightly. It is obvious that the shift of the Fermi energy, if occurs, should be the order of tens meV in magnitude. This result is interesting in the sense that it indicates a possibility to monitor the variation of Fermi level at the superconducting transition by accurately measuring the diffusion potential of YBCO-based heterojunctions. The gradual increase of the difference between the expected and observed V_d is also consistent with the fact that the superconducting band gap emergence at T_C and develops with the decrease of temperature. In fact, in the previous work on manganite junctions a significant change of diffusion potential starting at the ferromagnetic transition of the manganite was also observed, and explained as a result of the relative variation of Fermi level to the conduction band of the manganite.[3]

Compared with ordinary oxides, YBCO has a distinctive feature. Its energy band is determined not only by crystal structure but also by electron correlation, the latter yields the superconducting band gap below T_C. As a consequence, the band structure of the YBCO heterojunction is much complex. In addition to the band bending in space-charge region, the extra band gap associated with superconductivity may not occur in the junction region due to the depletion of charge carriers. The variation of depletion layer under applied bias, the influence of superconducting transition on the depletion layer due to the proximity effects are all interesting topics. Furthermore, bias voltage can modify the carrier density of YBCO especially near the YBCO/STON interface.[7,8] Although the main features of the $I-V$ relations may be determined by the mismatch of the band structures of YBCO and STON and carriers diffusion (the variation of carrier density in YBCO due to field effect is relatively small), the field effect on the detailed $I-V$ dependence is obviously an interesting issue deserving further investigations.

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