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Unusual transport behavior of the $SrTiO_3$-based homojunctions

W. M. Lü, J. R. Sun,[a] J. Wang, and B. G. Shen
Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China

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Two homojunctions composed of $La_{0.15}Sr_{0.85}TiO_3$ films and $SrTiO_3$:Nb substrates have been fabricated in the oxygen atmospheres of 10 and 20 Pa, respectively, and their transport behaviors are studied in the temperature range from 10 to 350 K. The most remarkable observations are the temperature independence of the current-voltage relations as well as the temperature/bias independence of the capacitance in the low temperature region in the junction obtained in an oxygen pressure of 10 Pa, and the exponential growth of current with reverse voltage. The rectifying behaviors can be well described by the Shockley equation at high temperatures, and the interfacial barrier, deduced from the current-voltage characteristics, are ~1.35 and ~0.73 eV, decreasing with oxygen pressure. The experiment results can be understood by assuming the formation of an insulating interfacial layer in the junctions. © *2009 American Institute of Physics*.
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$SrTiO_3$ is special in many aspects. It owns a cubic perovskite structure with a lattice constant of 3.905 Å, without phase transition down to 110 K. Due to the compatible lattice parameters, structures, and comparatively low chemical reactivity, it has been widely used as substrates for the perovskite films that show unconventional superconductivity, colossal magnetoresistance, and distinctive ferroelectricity. $SrTiO_3$ becomes conductive after partially replacing Ti/Sr with Nb/La, exhibiting a high mobility, about 10^3 $cm^2/V\ s$ at 10 K.[1] The electron-doped $SrTiO_3$ is an important ingredient of oxide heterojunctions that are important not only for practical application but also for fundamental research. Distinctive properties arising from the strong electric field dependence of the permittivity of $SrTiO_3$ have also been found in the corresponding junctions, such as electron tunneling-dominated rectification (Ref. 2) and polarity reversal of the current-voltage characteristics as temperature varies.[3]

Most of the previous works focused on the $SrTiO_3$-based heterojunctions. In this case, significant interfacial defects are inevitable due to the lattice mismatch of the two components of the junction, which sometimes cause a degeneration of the properties of the heterojunctions. $SrTiO_3$:Nb and La:$SrTiO_3$ are nearly exactly the same in every aspect. However, their electron affinity could be different due to the different element substitution.[4,5] This suggests the possibility to construct a homojunction with two perovskites that have excellently matched crystal structure, lattice parameter, and permittivity. In this letter, we first fabricated the homojunctions using the $SrTiO_3$:Nb substrates and the La:$SrTiO_3$ films with different carrier densities, then performed a systematic study on the transport property. In addition to the good rectifying behavior, the most remarkable observations are the temperature independence of the current density-voltage (*J*-*V*) characteristics and the temperature/bias independence of the capacitance in the low temperature region, as well as the exponential growth of the current with reverse voltage.

A $La_{0.15}Sr_{0.85}TiO_3$ (LSTO) target was prepared by the conventional solid-state-reaction technique. Subsequent x-ray diffraction analysis shows a clean perovskite structure with a lattice parameter of 3.899 Å. The homojunction was fabricated by growing a LSTO layer of 1500 Å on the 0.05 wt %Nb-doped $SrTiO_3$ (STON) substrate, which exhibits a lattice constant of ~3.905 Å, using the pulsed laser ablation technique from the ceramic target. The substrate temperature was kept at 700 °C and the oxygen pressure at 10 or 20 Pa during the deposition. The film thickness was controlled by deposition time. The samples thus obtained will be denoted as LSTO(10)/STON and LSTO(20)/STON, respectively. The oxygen content is homogeneous through the films as evidenced by the x-ray photoelectron spectroscopy analyses.

Two Cu pads were deposited, also by laser ablation, respectively on LSTO and STON as electrodes (junction area $=1\times1$ mm^2). The resistance is ~50 Ω for the Cu-LSTO contact and ~10 Ω for the Cu-STON contact. The *J*-*V* characteristics were measured by a superconducting quantum interference device magnetometer equipped with a resistance measurement unit. The bias directs from LSTO to STON is positive.

Figure 1 shows the semilogarithmic *J*-*V* characteristics of LSTO(10)/STON, measured in the temperature range be-

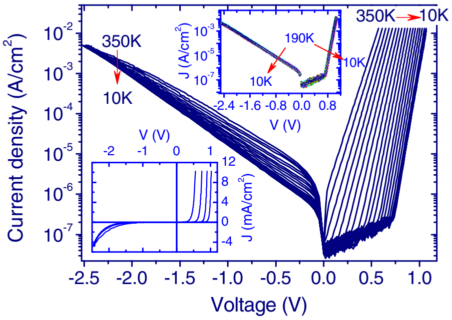

FIG. 1. (Color online) Semilogarithmic current-voltage characteristics of LSTO(10)/STON, measured in the temperature range from 10 to 350 K with a temperature step of 10 K. Top inset: *J*-*V* curves obtained from 10 to 190 K. Bottom inset: *J*-*V* curves in linear scale.

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[a] Author to whom correspondence should be addressed. Electronic mail: jrsun@g203.iphy.ac.cn.

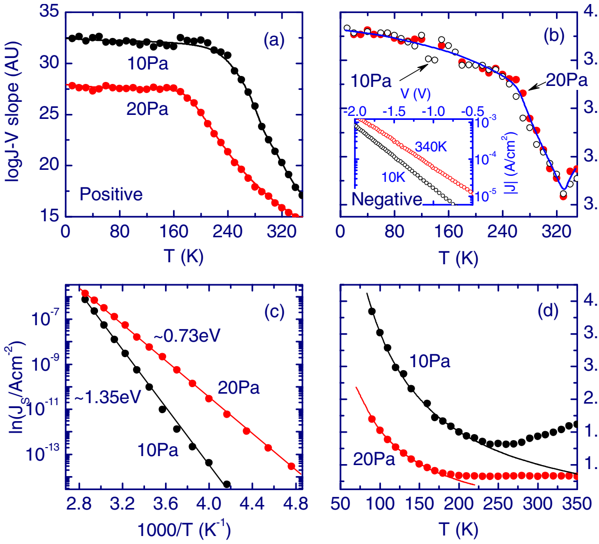

FIG. 2. (Color online) log$|J|$-V slope as a function of temperature for the LSTO/STON junctions under the forward (a) and reverse (b) biases. Inset plot in (b) is a close view of the reverse J-V curves at selected temperatures. (c) Saturation current as a function reciprocal temperature. (d) Ideality factor as a function of temperature. Solid lines in (d) denote the $1/T$ growth of the ideality factor.

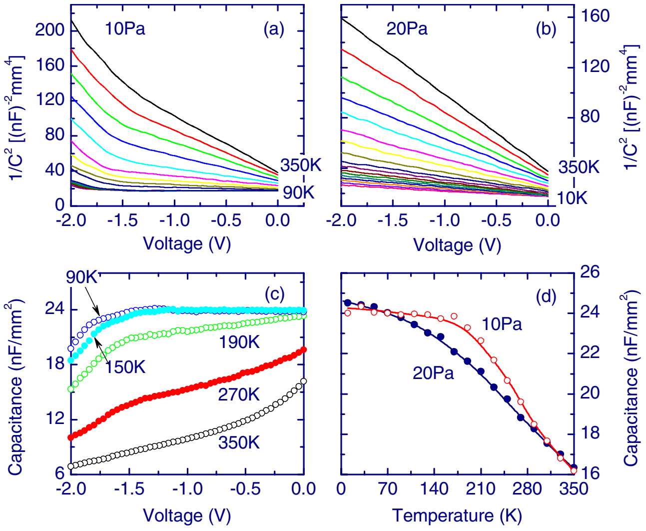

FIG. 3. (Color online) Reciprocal of square capacitance as a function of bias voltage for the LSOT(10)/STON (a) and LSTO(20)/STON (b) junctions, measured under the frequency of 200 kHz. (c) Capacitance as a function of bias voltage for the LSTO(10)/STON junction. (d) Temperature dependence of the zero-bias capacitance.

tween 10 and 350 K. The top inset is a close view of the J-V curves recorded between 10 and 190 K. A linear plot of selected data is presented in the bottom inset. At a first glance, LSTO/STON is similar to manganite junctions,[6] being well rectifying as demonstrated by the asymmetric J-V curves. However, substantial differences exist in detailed transport behaviors. The first unusual behavior for the present junction is the evolution of the J-V characteristics from thermionic emission to electron tunneling as well as the tendency toward temperature independence as temperature decreases. As shown in Fig. 2(a), with the decrease of temperature, the log J-V slope first grows rapidly, which is a feature of the thermal process, then stabilizes at a constant value, which is a signature of electron tunneling. An exact overlap of the J-V curves is further observed below 190 K, under either positive or negative biases (top inset in Fig. 1). The latter is a phenomenon unreported before for either homo- or heterojunctions. It reveals not only the dominant role of electron tunneling in the transport process but also the invariance of the interfacial state as temperature varies. Similar phenomena are observed in the LSTO(20)/STON junction except for minor differences in detailed J-V dependence.

The second remarkable observation is the linear relation between log$|J|$ and reverse biases. As shown by Fig. 2(b) and the inset plot, the log$|J|$-V curves are linear in the whole temperature range investigated. With the decrease of temperature, the log$|J|$-V slope reduces first fairly rapidly then slowly, with a visible inflection at ~250 K. Unlike the cases under positive biases, the log$|J|$-V slopes of LSTO(10)/STON and LSTO(20)/STON completely overlap. This result indicates the similarity of the two junctions as depletion thickness grows, considering the expansion of the depletion width under reverse biases.

To get the information on interfacial state, saturation current J_S is further analyzed. A nearly exponential growth of J_S with T is observed above the temperature of 250 K, for LSTO(10)/STON, and 200 K, for LSTO(20)/STON [Fig. 2(c)], which confirms the thermal activation character of J_S. As well established, there is a simple relation between saturation current and interfacial barrier,[7] $J_S \propto \exp(-q\Phi_B/k_BT)$, where q is the electron charge, Φ_B the interfacial barrier, and k_B the Boltzmann constant. Based on the data in Fig. 2(c), the interfacial barrier can be obtained, and it is ~1.35 eV for LSTO(10)/STON and ~0.73 eV for LSTO(20)/STON. The increase of oxygen content in LSTO(20) causes a dramatic decrease of interfacial potential. This is plausible noting the similarity of LSTO and STON in the limit without electron doping.

The ideality factor n is shown in Fig. 2(d), as a function of temperature. It closes to two for LSTO(10)/STON while unity for LSTO(20)/STON in the temperature region above 200 K. The large ideality factor in LSTO(10)/STON implies either considerable interfacial inhomogeneity or enhanced recombination of charge carriers in the junction region, which is understandable considering the existence of excessive defects due to oxygen depletion. The increase of the ideality factor in the low temperature region, following the formula of $n \propto 1/T$ (marked by solid lines), could be a signature of electron tunneling.

To get the information about depletion layer, a systematic study on capacitance (C) was performed. Figures 3(a) and 3(b) exemplify the capacitances of LSTO(10)/STON and LSTO(20)/STON, respectively, measured under the frequency of 200 kHz. Well defined $1/C^2 \propto V$ relations are observed at the temperatures above 250 K for LSTO(10)/STON and in the whole temperature range for LSTO(20)/STON, which is the typical feature of homo- or heterojunctions.[6] However, for LSTO(10)/STON, the C-V curve flattens rapidly as temperature decreases, and finally becomes bias independent below 190 K. This is a feature unexpected for the junction [Fig. 3(c)]. Figure 3(d) shows the temperature dependence of the capacitance, obtained in the zero-bias limit. With the decrease of temperature, the capacitance of LSTO(10)/STON exhibits first a smooth growth then a gradual saturation, at a value of ~24.1 nF/mm². The constant capacitance is the further evidence for the temperature independence of the interfacial layer, consistent with the conclusion drawn from the *J*-*V* curve analysis. These features can also be identified from the *C*-*V* relations of LSTO(20)/STON, though they are not as typical as those observed in LSTO(10)/STON.

The Hall effect study of the LSTO film shows the electron character of the charge carrier in the LSTO films and the STON substrates, and the carrier density is, at the ambient temperature, $\sim 3.4\times 10^{20}/\mathrm{cm}^3$ for the LSTO(10) film (Ref. 8) and $\sim 6\times 10^{18}/\mathrm{cm}^3$ for the STON substrate. This result indicates that the homojunctions are Schottky junctions, and the LSTO film acts as a metallic electrode. The formation of the junction reveals the difference of the Fermi level of LSTO and STON, and the Fermi level of the former is lower than that of the latter. This is a conclusion different from that of Ref. 4. In general, the introduction of large ions can cause a growth of Fermi level.[9] Nb^{5+} is larger than Ti^{4+} whereas La^{3+} is smaller than Sr^{2+}. This may explain the larger electron affinity of LSTO than that of STON. The dramatic change of Φ_B as oxygen content in LSTO increases may indicate the growth of the electron affinity of LSTO.

According to the semiconductor theory,[7] the capacitance of the Schottky junction has the form of $C\approx[qN_D\varepsilon_0\varepsilon/(V_d-V)]^{1/2}$, where V_d is the diffusion potential ($V_d\approx\Phi_B$ for the LSTO/STON junction). It suggests an inevitable capacitance variation with bias voltage, which is different from the detected flatten *C*-*V* relationship in LSTO(10)/STON [Fig. 3(c)]. A constant capacitance can be obtained only when $\varepsilon_0\varepsilon/(V_d-V)$ is constant or an insulating interfacial layer with a much smaller capacitance than the depletion layer exists. The former is unlikely since it requires a special bias dependence for the permittivity. In the presence of an interface layer, the total capacitance will be $C=C_iC_d/(C_i+C_d)$, where C_i and C_d are the capacitances of the interfacial layer and the depletion layer, respectively. When $C_d\gg C_i$ the principal capacitance will be approximately C_i. In this scenario, the interfacial capacitance, deduced from the data in Fig. 3(d), will be $\sim 24\ \mathrm{nF/mm}^2$. The growth of the capacitance of the depletion layer upon cooling could be ascribed to the enhancement of the permittivity of SrTiO_3.

The present work suggests the presence of a special interfacial layer. We noted that a surface depletion that yields an insulating layer has been observed by Ohtomoa and Hwang[10] in the $\mathrm{La}_{0.05}\mathrm{Sr}_{0.95}\mathrm{TiO}_3$ films grown on STO. These results reveal the distinctiveness of SrTiO_3.

According to the semiconductor theory, the electronic transport in the Schottky junction is determined by the thermionic emission or electron tunneling process. The forward bias voltage can help the charge carrier to conquer or penetrate through the interfacial barrier, causing an exponential current growth. The overlap of the *J*-*V* curves below 190 K in LSTO(10)/STON indicates the temperature independence of the transport process. In this case, the electronic transport in the junction may proceed via the electron tunneling described by $J\propto\exp(qV/E_{00})$. In addition to reducing the current by a factor of $\exp(-\alpha\delta)$, the insulating interface layer would not affect the *J*-*V* dependence after replacing V by V/n (only part of the applied voltage drops on the depletion layer), where α is a constant and δ is the thickness of the interfacial layer. The difference between the calculated and observed E_{00}'s may also suggest the presence of this layer. Based on the formula $E_{00}=qh/4\pi(N_D/m^*\varepsilon_0\varepsilon)^{1/2}$,[6] E_{00} can be calculated. It is ~ 4.7 meV, adopting the parameters $h=6.626\times 10^{-34}$ J s, $q=1.6\times 10^{-19}$ C, $\varepsilon=100$,[11] and $m^*\approx 9.1\times 10^{-31}$ kg. It is smaller than the E_{00} value deduced from the *J*-*V* curves in the low temperature region (~ 31.3 meV) by a factor of ~ 4. In fact, in the presence of an insulating layer, the log *J*-*V* slope may not be a direct measure of $1/E_{00}$. It overestimates E_{00} by a factor of n. As experimentally shown, the ideality factor of LSTO(10)/STON grows from ~ 2 to ~ 3.6 as temperature decreases from ~ 200 down to 90 K.

As for the electronic transport under reverse biases, it could be a thermionic-field emission process noting the linear dependence of log *J* on *V*.[6] However, the apparent log *J*-*V* slope shows a tendency to saturation as temperature decreases, instead of monotonically growth, $[(E_{00}/k_BT)-\tanh(E_{00}/k_BT)]/E_{00}$, as expected by the semiconductor theory. This may also ascribed to the partial voltage drop on the insulating layer.

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[11] From the Eq. (6) in Ref. 3, the permittivity of SrTiO_3:Nb in a junction can be calculated as a function of the distance from the interface. The minimal value of ε is ~ 100 at 100 K, occurring at the interface. The actual value may be even large due to the depression of the built-in field by the insulating layer.