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We report the fabrication of heterojunctions formed by the $FeSe_{0.5}Te_{0.5}$ (FeSeTe) superconductor and Nb-doped $SrTiO_3$ semiconducting substrate and their properties. At high temperature when FeSeTe is in its normal state, the forward bias $I-V$ curves behave like a metal-semiconductor junction with a low Schottky barrier. Direct tunneling through the thin depletion layer of the junction dominates the reverse bias $I-V$ curves. When FeSeTe film becomes superconducting at low temperature, we observed that the Schottky barrier height of the junction increased but was suppressed by an external magnetic field. This deviation provides an estimate of the superconducting energy gap of the FeSeTe film. © *2010 American Institute of Physics*.
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The recently discovered Fe-based superconductors have attracted great attention.[1–3] Among these, FeSe, which has the simplest crystal structure, could be an ideal system for better understanding the mechanism responsible for superconductivity in the Fe-based materials.[4] Doping FeSe with Tellurium enhances T_c, and $Fe(Se_{1-x}Te_x)$ (hereafter FeSeTe) superconducting thin films with c-axis preferred orientation can be prepared on several kinds of substrates.[5–8] These films have been found to have multi-band characteristics. When lightly Nb-doped $SrTiO_3$ (hereafter NSTO), which is an n-type semiconductor,[9] is used as a substrate, a superconducting/semiconducting (S/Sm) heterojunction can be formed. Previously, heterojunctions using $YBa_2Cu_3O_7$(YBCO)/NSTO have been investigated.[10,11] It will be interesting to investigate in more detail how the interface of Fe-based superconductor and semiconductor behaves. In this letter, we report the $I-V$ characteristics of FeSeTe on NSTO heterojunctions at temperatures above and below the superconducting transition. Shifts in the Schottky barrier height (SBH) below the FeSeTe superconducting transition allow an estimate of the superconducting energy gap of ~2.06 meV.

The FeSeTe films were prepared by pulsed laser deposition (PLD) technique on 0.05 percentage weight (wt %) NSTO single crystal substrates. The detailed deposition parameters were described previously.[5] The crystal structure of the FeSeTe thin films were characterized with an x-ray diffractometer. The junctions were patterned into an area of roughly 8 mm^2 by ion miller. Temperature dependence of resistivity of the thin films and current-voltage ($I-V$) characteristics of the junctions were measured by four-point method.

The x-ray diffraction (XRD) pattern of FeSeTe thin film on NSTO substrate is shown in Fig. 1(a). Only (00*l*) diffraction peaks were observed, indicating good c-axis preferred orientation of the thin films. Figure 1(b) shows the temperature dependence of resistivity of FeSeTe thin film. The resistivity has a maximum value near 210 K and a sharp superconducting transition at 9 K, which is consistent with earlier results on MgO substrate.[4] The inset illustrates the $R-T$ curve of 0.05 wt % NSTO substrate. Its carrier density is estimated to be 2×10^{19} cm^{-3} at 300 K.[12]

The $I-V$ curves of FeSeTe/NSTO heterojunction were measured by a configuration as shown in the lower right inset of Fig. 2. Figure 2 displays the $I-V$ curves of the junction at temperatures above FeSeTe superconducting transition. The $I-V$ curves exhibit current rectifying and asymmetric characteristics in both forward and reverse biases. Two features of these $I-V$ curves deviate from the behavior of a typical Schottky barrier. For forward current region, a linear $I-V$ region was observed at low bias voltage indicating the thermionic emission current should be small. The excess current could be due to the tunneling of electrons through some localized low energy states in the transition layer of FeSeTe

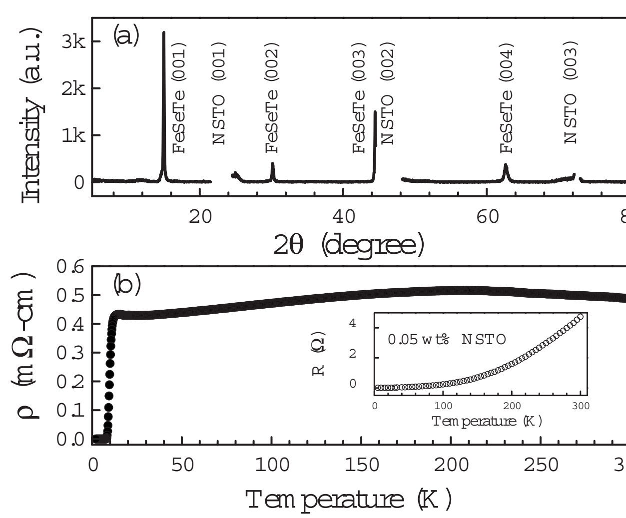

FIG. 1. (a) The x-ray diffraction pattern of $FeSe_{0.5}Te_{0.5}$ film deposited on the (100) oriented NSTO substrate at substrate temperature 320 °C. Only (00*l*) peaks were observed, which indicates preferred c-axis orientation of the film. (b) The temperature dependence of resistivity of $FeSe_{0.5}Te_{0.5}$ film on NSTO. A sharp superconducting transition was observed near 9.5 K. The inset shows the temperature dependence of resistance of NSTO substrate.

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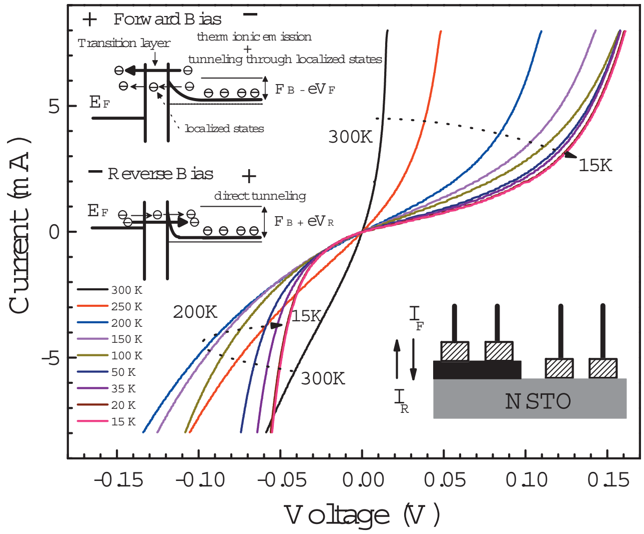

FIG. 2. (Color) The $I-V$ curves of the FeSeTe/NSTO heterojunction at temperature from 300 to 15 K. The lower right inset demonstrates the schematic diagram of the junction and measurement configuration. The upper left inset shows the possible processes of electrons passing through the junction in forward and reverse bias at low temperature respectively.

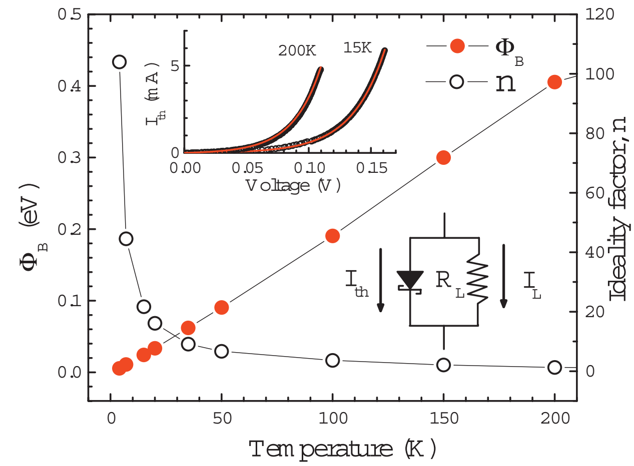

FIG. 3. (Color) The main frame shows the temperature dependence of extracted SBH (Φ_B) and ideality factor (n). The SBH is relatively low and decreases linearly at low temperature. The ideality factor increases quickly at low temperature. The lower right inset shows the analyzing model of the junction. The shunted resistor represents the tunneling process through the localized states at interface. The upper inset illustrates the experimental data and fitting curves. The data can be fitted very well in the forward bias region by thermionic emission theory.

film near the interface or the oxygen vacancies at NSTO substrate surface. On the other hand, the reverse bias $I-V$ curves behave anomalously as temperature decreases. It first shifts to higher voltage bias as temperature decreases and turns back to lower bias voltage at lower temperatures. Similar anomalous behavior was reported in In/STO/NSTO junctions,[13] where the reverse current at low temperature was dominated by direct tunneling process because of the reduction of depletion layer width due to high carrier density at the STO/NSTO interface. In FeSeTe/NSTO junctions, we believe the low SBH results in a thinner depletion layer, thus, enhancing tunneling processes under reverse bias. These observations can be understood in terms of the energy diagram for FeSeTe/NSTO junctions at low temperature, which is schematically illustrated in the upper left inset of Fig. 2.

We utilize an equivalent circuit based on the general thermionic emission model[14,15] to simulate the junction as shown in the lower right inset of Fig. 3. A shunted resistor, R_L, was used to represent the tunneling process through those low energy localized states. We could then extract the characteristic parameters of the junction from the measured $I-V$ curves using this model. The upper inset shows good fitting of forward $I_{th}-V$ curves between measured data (circles) and theoretical curves (solid lines) at temperatures of 200 and 15 K, where I_{th} is the current passing through Schottky barrier by thermionic emission process. The main feature of Fig. 3 presents the temperature dependence of SBH (Φ_B) and ideality factor (n). A Richardson constant of 156 A cm^{-2} K^{-2} was used for 0.05 wt % NSTO as a known parameter.[16] We found that Φ_B decreases almost linearly from 402 meV at 200 K to 24.7 meV at 15 K. The strong temperature dependence of SBH, −2 meV/K, is likely due to the lateral nanoscale SBH inhomogeneity, as has been proposed for YBCO/NSTO[10] junctions. Inhomogeneities could result from factors such as strain, chemical composition, interface topological fluctuations, or defect distributions. The ideality factor increases from $n=1.3$ at 200 K to 20.6 at 15 K. The increase in ideality factor is similar to the results reported in Au/NSTO and LSMO/NSTO junctions, which were attributed to the presence of an intrinsic low permittivity layer at STO surface and the increase in the dielectric constant of STO at low temperature.[17,18]

Below 9 K, FeSeTe film becomes superconducting so that now the FeSeTe/NSTO heterojunction is an S/Sm junction. The $I-V$ curves shift toward a higher bias voltage, as shown in Fig. 4(a), which is attributed to the evolution of superconducting energy gap of FeSeTe film. Comparing with the results reported in YBCO/NSTO (S/Sm) junction,[11] the shift in $I-V$ curves in our FeSeTe/NSTO S/Sm junction is much clearer. By using similar method, we obtained the value of SBH at 7 and 4.2 K. The inset shows the deviation of SBH from the linearly extrapolated value based on the data at high temperature. The deviation of SBH close to the

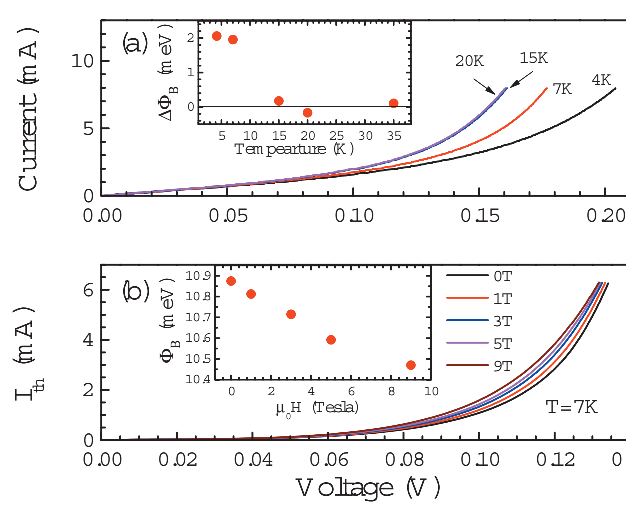

FIG. 4. (Color) (a) The $I-V$ curves of the FeSeTe/NSTO heterojunction at low temperature. When FeSeTe becomes superconducting, the $I-V$ curves clearly shift to higher bias voltage. The inset shows the deviation of SBH from the linearly extrapolated value based on the data at high temperature. (b) The forward $I_{th}-V$ curves at temperature 7 K under magnetic field up to 9 T. The shift in $I-V$ curves was suppressed gradually by magnetic field. The inset shows SBH decreased monotonically because of superconducting gap suppression by external magnetic field.

superconducting energy gap of FeSeTe at 4.2 K is about 2.06 meV, which is comparable to the recently reported value of 2.3 meV by STM experiment.[19] Figure 4(b) shows that the shift in $I-V$ curves at 7 K is gradually reduced as the external magnetic field is increased. As shown in the inset, SBH decreases monotonically as external magnetic field increases, which is associated with the suppression of superconducting energy gap.

In conclusion, we fabricated high quality FeSeTe/NSTO heterojunctions by PLD technique. The FeSeTe/NSTO junctions can be described by a metal-semiconductor Schottky barrier junction with a shunted resistor. The shunted resistor might result from the tunneling of electrons through the lower energy localized state in the imperfect interface. The junction SBH is relatively low, ~400 meV at 200 K, compared to other metal/NSTO junctions and has strong temperature dependence, about −2 meV/K. The ideality factor increases quickly at low temperature, which was attributed to the imperfect interface. In reverse bias region, the junction current is dominated by direct tunneling of electrons through the thin depletion layer. At low temperature, the FeSeTe/NSTO junction transitions into an S/Sm junction. The SBH becomes higher due to the presence of the FeSeTe superconducting energy gap, which is estimated to be about 2.06 meV at 4.2 K.

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