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Transport properties in FeSe_{0.5}Te_{0.5} nanobridges

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FeSeTe nanobridges of different widths have been fabricated on MgO substrates using focused ion beams. These nanobridges exhibit the Josephson effects. The current-voltage curves of junctions with 248–564 nm wide follow the resistively and capacitively shunted junction model. Shapiro steps under microwave radiation were clearly observed in these nanobridges. The products of the critical current and normal state resistance (I_cR_n) are remarkably high. The temperature dependence of I_cR_n product followed the Ambegaokar-Baratoff (A-B) relation. The value of energy gap of FeSeTe calculated from the A-B relation is 3.5k_BT_c. The nanobridge junctions have a strong potential for high frequency applications. © 2013 AIP Publishing LLC [http://dx.doi.org/10.1063/1.4809920]

The iron-based superconductors have been extensively investigated since their discovery became a surprise to the superconductivity research community. 1–8 Josephson effects and their applications in iron-based superconductors were also reported. 1,2 However, certain properties of various iron-based superconductors have yet to be elucidated, such as the coupling mechanisms of Cooper pairs in iron-based superconductors. Planar Josephson junctions of iron-based superconductors have also not been widely investigated. To date, only two types of Josephson junctions of Fe-based superconductor thin films have been studied. One was fabricated with a bicrystal grain boundary, 3 and the other used an superconductor–normal metal–superconductor (SNS) structure of BaFe_2As_2:Co thin film. 4 Shapiro steps were clearly observed with those junctions, indicating the possible application of such materials in Josephson devices. The magnetic field and temperature-dependence of I_c have been measured, and the structures of junctions have been observed with high-resolution transmission electron microscopy (HR-TEM), showing that the Josephson junctions of iron-based superconductors behave like the SNS junctions.

In this study, the transport properties, Josephson effects, and energy gaps of FeSeTe nanobridges made by focused ion beams (FIB) are investigated.

The properties of bulk FeSe_xTe_{1-x} have been studied. 5–8 The superconductivity in FeSe_xTe_{1-x} (FeSeTe) varies with x, and the critical temperature is highest when x equals 0.5. High quality FeSeTe thin films are typically deposited by Pulsed Laser Deposition (PLD). The critical temperature depends on the film thickness and the substrate material. 9 In this work, the FeSeTe thin film with a thickness of 100 nm on a MgO substrate is also prepared by PLD. The grown FeSeTe thin film has favorable superconducting properties with a critical temperature T_c of 14.6 K. To protect the thin films and to increase the accuracy in dimensions of junctions, a gold layer is deposited by a DC sputtering system on top of the FeTeSe thin film before the FIB process. The Au layer also provides low contact resistance and high conductivity on the surface of the FeSeTe thin film. To form the junction, FeSeTe bridges with a width of 8 μm are constructed by standard photolithography and Ar ion milling, and the nanobridges of a width less than 1 μm are subsequently formed via FIB etching. The electrical properties are measured using a four-probe technique.

Figure 1 presents a scanning electron microscopic (SEM) image of the nanobridges with a width of 564 nm. To reduce the damage caused by containment of gallium ions, the dwell time and passes of ion beam were optimized during the FIB machining process.

Figure 2 shows the voltage-current (V–I) characteristic and the fit curve to the resistively and capacitatively shunted-junction (RCSJ) model for the nanobridge of

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FIG. 1. SEM images of a FeSeTe nanobridge fabricated by FIB.
564 nm width. By using the RCSJ model, the current passing through the junction is

\[ I = C \frac{dV}{dt} + GV + I_c \sin \varphi, \]

where \( C \) denotes the capacitance, \( G \) is the conductance, and \( I_c \) is the Josephson supercurrent. The McCumber parameter, \( \beta_c = 2\pi e^2 R C / \Phi_0 \), is found to be less than 0.65, where \( R \) and \( C \) are, respectively, the normal resistance and equivalent capacitance of the junction, while \( \Phi_0 \) is the flux quantum. All of the \( V-I \) characteristics of nanobridges with different widths were found to agree closely with the RCSJ model.

Over the past few decades, FIB-milled nanobridge junctions made of various superconductors, e.g., YBCO, Nb, and MgB$_2$, have been reported. However, with our device, Shapiro steps are observed when 248–564 nm wide nanobridges are irradiated with microwaves. Figure 3 shows that the microwave irradiation suppresses \( I_c \), and Shapiro steps are observed when a 564 nm wide nanobridge is irradiated with microwaves at 7.8 GHz. The step height is found to be 16 \( \mu \)V, in agreement with the relation \( V = hf/2e \), where \( h \) is the Plank’s constant and \( e \) is the elementary charge. The \( V-I \) characteristics of the FeSeTe nanobridges herein are similar to those of the Fe-based bicrystal junctions, \( \sin \), the magnitude of the critical current is approximately 1 mA with a small excess current, and \( V-I \) characteristics have minor or no hysteresis. We believe that some grain boundaries in the nanobridges are responsible for the weak link behavior. The nanobridges of 150 nm width have been fabricated, but the critical currents are very small, and Shapiro steps cannot be observed.

Table I presents the values of \( I_c \), \( R_n \), and \( \beta_c \) obtained from the \( V-I \) characteristics of nanobridges fitted by the RCSJ model. The values of \( I_c \) and \( I_{ex} \) increase with the width of the nanobridge. The \( R_n \), which ranges from 5.2 to 7.0 \( \Omega \), and \( \beta_c \), also depends on the width. The \( \beta_c \) of 672 nm wide nanobridge is 0.65. A capacitance of 2.9 pF was derived using the McCumber equation. This is larger than the capacitances of the other nanobridges (with widths 564 nm, 384 nm, and 248 nm).

The value of \( \beta_c \) for the 564 nm wide nanobridge is 0.3, and the \( V-I \) curve exhibits slight hysteresis. At \( T = 4.2 \) K, the critical current \( I_c \) is 880 \( \mu \)A with an excess current of \( \sim 40 \) \( \mu \)A, and the normal resistance is 6.8 \( \Omega \). The \( I_c R_n \) product is approximately 6.0 mV. The value of \( I_c R_n \) is quite large, as it is for other superconducting materials, such as the MgB$_2$ break junction. \( \beta_c \). The \( \beta_c \) values of nanobridges with widths of less than 564 nm are small, and the nanobridge with a width of 384 nm is negligibly small and not observable.

Figure 4 plots the \( V-I \) and \( dV/dI \)-versus-\( I \) characteristics of the 564 nm wide FeSeTe nanobridge at temperatures from 12.3 K to 4.2 K. The critical temperature and the critical current are, respectively, 12.3 K and 100 \( \mu \)A. The critical currents of 835 \( \mu \)A and 880 \( \mu \)A correspond to temperatures of

<table>
<thead>
<tr>
<th>Width of nanobridges</th>
<th>( I_c ) (( \mu )A)</th>
<th>( R_n ) (( \Omega ))</th>
<th>( I_{ex} ) (( \mu )A)</th>
<th>( \beta_c )</th>
<th>( C ) (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>428 nm, ( T = 4.2 ) K</td>
<td>880</td>
<td>6.8</td>
<td>40</td>
<td>0.3</td>
<td>2.7</td>
</tr>
<tr>
<td>384 nm, ( T = 4.2 ) K</td>
<td>660</td>
<td>5.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>564 nm, ( T = 4.2 ) K</td>
<td>880</td>
<td>6.8</td>
<td>40</td>
<td>0.3</td>
<td>2.7</td>
</tr>
<tr>
<td>672 nm, ( T = 4.2 ) K</td>
<td>1380</td>
<td>6.2</td>
<td>130</td>
<td>0.65</td>
<td>2.9</td>
</tr>
</tbody>
</table>

\( *I_c \) is the critical current of nanobridges.

\( *R_n \) is the normal resistance of nanobridges.

\( *I_{ex} \) is the excess current of nanobridges.

\( *\beta_c \) is the McCumber \( \beta_c \) of nanobridges.

\( *C \) is the capacitance of nanobridges.
6.5 K and 4.2 K, and the critical current at 3.9 K is close to 880 µA. The small change in critical current of the nanobridge was observed when the temperature is below 6.5 K, which is about half of the critical temperature \( T_c = 12.6 \) K.

Figure 5 plots the temperature-dependence of the \( I R_n \) product. The relationship between temperature and \( I R_n \) is found to follow the Ambegaokar-Baratoff relation \(^{12}\)

\[
I R_n = \frac{\pi \Delta(T)}{2 e} \tanh \left( \frac{\Delta(T)}{2 k_B T} \right),
\]

where \( e \) is the elementary electric charge, \( \Delta(T) \) is the temperature-dependent superconducting energy gap, and \( k_B \) is the Boltzmann constant. Generally, the A-B relation is used to describe tunneling Josephson junctions exhibiting stable superconducting properties at temperatures below \( T_c/2 \) with a large \( R_n \) and \( I R_n \) product, which is promising for SQUID and high frequency applications. Since the magnitude of the peak-to-peak \( (V_{pp}) \) voltage of SQUID is positively correlated with the normal resistance \( (R_n) \), it is interesting to verify the properties of the SQUID comprising such junctions. The high frequency sensor can be fabricated using Josephson junctions with large \( I R_n \) products, when a junction is irradiated with microwaves at 0.1 THz, the Shapiro step height is 207 µV, in agreement with the relation \( V = hf/2e \).

From past experience, the temperature-dependence of the critical current in YBCO, MgB2, and BaFeAs:Co nanobridges fabricated by FIB is similar to that of the bicrystal junction, and it reveals SNS behavior. For the SNS and bicrystal junctions, the critical current increases as the temperature decreases in proportion to \( 1 - (T/T_c)^\alpha \), where \( \alpha = 1 \) or 2 (at high temperatures). However, the data obtained in the current study differ from those obtained for a bicrystal and SNS junction.

The solid line in Fig. 5 shows the superconducting energy gap of the FeSeTe nanobridge that was calculated from the A-B relation. The curve of the fitted energy gap as a function of temperature is consistent with the energy gap of the BCS-type temperature dependence.\(^{13}\) However, this superconducting energy gap, which did not match the experimental, was calculated using the formula of the SNS-long junction and the \( I R_n \) product at various temperatures

\[
I_c(T; L) = \frac{2}{\pi e R_n} \frac{|\Delta(T)|^2}{k_B T_c} \frac{L/\xi}{\sinh(L/\xi)} ,
\]

where \( L \) is the barrier thickness of the junction and \( \xi \) is coherence length of the thin film. The value of \( \Delta(T) \) for the FeSe0.55Te0.45 nanobridges of 564 nm width is 3.5 \( k_B T_c \).

Superconducting energy gaps of FeSeTe \( I R_n \) can be determined using various methods. For example, the energy gap of the heterojunction is estimated to be 2.06 meV,\(^{14}\) but an energy gap of 2.3 meV is measured by STM.\(^{15}\) Accordingly, the calculated 2\( \Delta \)/\( k_B T_c \) is 3.8, which is close to the value based on BCS theory. The point-contact Andreev reflection (PCAR) method, in which the energy gap is calculated from \( dI/dV \), reveals strong coupling superconductivity in the FeTe0.55Se0.45 thin film. The energy gap is 3.8 meV at 1.7 K. The superconducting energy gaps that were calculated with the \( I R_n \) products agree with that calculated using the PCAR method.\(^{16}\) Our data are similar to that of FeSeTe break junctions, which were investigated by Park.\(^{16}\)

In summary, FeSeTe nanobridges were fabricated with widths from 248 to 672 nm on MgO substrates using a FIB. The current-voltage characteristics reveal that the critical currents of the nanobridges increase as the temperatures decreases, but the variation in the critical current is small and below 0.5\( T_c \). The \( I-V \) characteristics can be fitted by the RCSJ-model with a small excess current and a slight hysteresis, whereas the temperature-dependence of critical current can be fitted by the Ambegaokar-Baratoff relation. The superconducting energy gap of the FeSeTe nanobridges is 3.5\( k_B T_c \). The effect of microwave irradiation on the junctions is clearly observed. Further work to investigate the techniques for trimming the parameters of FIB FeSeTe junctions would be valuable for device applications.