Observation of Tomasch oscillations and tunneling-like behavior in oxygen-deficient edge junctions

O. Nesher[a] and G. Koren
Physics Department, Technion–Israel Institute of Technology, Haifa 32000, Israel

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Properties of oxygen-deficient edge junctions made of $YBa_2Cu_3O_{6.6}$ as the superconductor and $YBa_2Cu_{3-x}Fe_xO_y$ as the barrier are reported. These junctions show weak-link characteristics when the edge angle is 50°, while tunneling-like behavior is observed when the edge angle is 36°. In all junctions strong peaks in the conductivity are found, which depend on the specific junction geometry. Some series of peaks were identified as due to Tomasch oscillations in the cover electrode, which yield $\Delta=1.4\pm0.2$ meV and $v_F'=(4.4\pm0.2)\times10^7$ cm/s. © *1999 American Institute of Physics.* [S0003-6951(99)04522-2]

One of the goals since the discovery of the high-T_c superconductors has been to obtain superconductor–insulator–superconductor (SIS) tunneling junctions. Such junctions could be useful for basic research as well as for potential practical applications. Unfortunately, prefabricated tunneling junctions are not available yet, and most of the tunneling experiments have been done using point-contact scanning tunneling microscopy, break junctions, and grain-boundary (GB) junctions.[1–3] All these experiments are difficult to reproduce, there is almost no control of the barrier, and the geometry is not well defined. SIS junctions made of thin films of the high-T_c superconductors are clearly very desirable since they should allow us to control the geometry and the barrier of the junction. However, such junctions made, for instance, with $YBa_2Cu_3O_{7-\delta}$ (YBCO) electrodes, are difficult to make. This is due to the short coherence length of YBCO of about 1.5–2 nm, which leads to a large depression of the order parameter at the SI interface.[4] A possible way to overcome this problem is to use oxygen-deficient films with a reduced T_c, which therefore, have a longer coherence length.[5] We have already found in the past that YBCO-based junctions with $YBa_2Cu_2CoO_y$ as the barrier show a transition from weak-link to tunneling-like behavior, when their oxygen content is reduced.[6] These junctions, however, had a poorly defined wedge-edge geometry and we, therefore, decided to use in the present study the standard edge junction geometry, which is well defined. This time, we observed a transition from weak-link to tunneling-like behavior as a function of the edge angle, as well as resonances in the dynamic conductance which are attributed to Tomasch oscillations.

Barrier materials in YBCO-based junctions should be compatible with YBCO, and if tunneling is expected, they should also have high resistivity. Such materials can be found in the YBCO derivative family, which was intensively investigated in the past. Heavily doped YBCO yields better insulators, which generally suffer from lattice-mismatch problems with YBCO, or do not grow with *c*-axis orientation normal to the substrate. In the present study we choose $YBa_2Cu_{3-x}Fe_xO_y$ with $x=0.3$, 0.45, or 0.6 as a barrier (YBCFeO), since these materials are less heavily doped but still have a sizable resistivity. The various Fe-doped YBCO films were investigated for compatibility with pure YBCO and $SrTiO_3$ (STO) and found to grow on one another fully epitaxially.[7] Figure 1(a) shows the resistivity of thin films of $YBCFe_xO$ on STO, with *x* values of 0.3, 0.45, and 0.6. All these films were deposited by laser ablation deposition under the same conditions as for YBCO. They showed good crystallinity and epitaxial growth with *c*-axis orientation normal to the wafer. Next, we prepared oxygen-deficient $YBCFe_xO$ films under the same conditions as the oxygen-deficient YBCO is made ($YBa_2Cu_3O_{6.6}$, $T_c=60$ K). These films were cooled down immediately after deposition under 40 mTorr of oxygen flow, at a rate of 0.25 °C/s. Figure 1(b) shows the

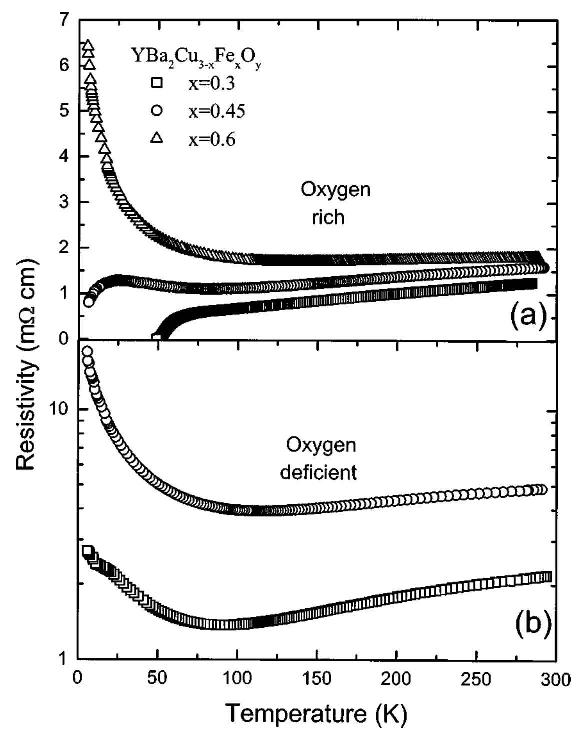

FIG. 1. Resistivity of 150 nm thick films of $YBa_2Cu_{3-x}Fe_xO_y$ which were cooled down right after the deposition process in either (a) 0.5 atm O_2 or (b) 40 mTorr O_2.

[a]Electronic mail: onesher@physics.technion.ac.il

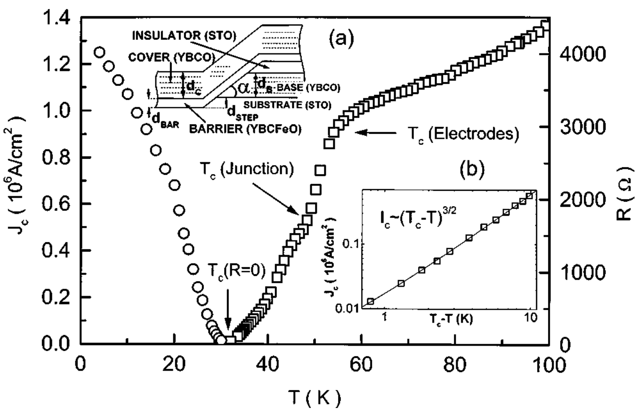

FIG. 2. Resistance and critical current of an oxygen-deficient edge junction without a barrier (a short) as a function of temperature. Inset (a) shows a schematic diagram of an edge junction. Inset (b) shows the critical current J_c as a function of reduced temperature T_c-T on a log–log scale.

resistivity of these thin films with $x=0.3$ and 0.45. One can see that these films are insulating at temperatures lower than 90 K, which makes them appropriate barriers for the oxygen-deficient junctions. The oxygen-deficient film with $x=0.6$ had microcracks due to strain between the film and the substrate, and thus, its resistivity versus temperature is not shown in Fig. 1(b).

The geometry of an edge junction is described schematically in inset (a) of Fig. 2. Such junctions were prepared using our standard multistep process. First, the base electrode and insulator films were prepared *in situ* by laser ablation deposition on a 1×1 cm^2 (100) STO wafer. Then, the sample was patterned using a *waterless* process with PMMA resist and deep UV photolithography. Etching was done by Ar-ion milling that produced an edge angle α. Next, the barrier, the cover electrode, and a gold film for the contacts were deposited, and the sample was patterned into ten 5 μm wide junctions. To test the reliability of our process we also prepared well-oxygenated ''shorts,'' which are edge junctions *without* a barrier. The T_c's of these shorts were found to be in the range between 87 and 88 K, and the average J_c at 77 K was 2.5×10^6 A/cm^2 with one standard deviation spread of 20% for ten shorts on the same wafer. These results indicate that the contacts between the two electrodes were clean and quite reproducible in all ten shorts. These results where obtained with $\alpha=50°$. With $\alpha=36°$, however, the average J_c was only 0.5×10^6 A/cm^2 at 77 K.

The next step was to check shorts made of oxygen-deficient YBCO. In Fig. 2, typical transport results of these shorts are shown. One can see that the transition of the YBCO electrodes is at about 55 K, while the contact area between the electrodes has a broad transition between 50 and 30 K. We attribute this wide transition range to a nonuniform oxygen distribution in the contact cross section.[8] A possible reason for this behavior is that the contact area loses oxygen far more easily than the bare YBCO film. Inset (b) in Fig. 2 shows that J_c of this ''short'' is proportional to $(T_c-T)^{3/2}$ with $T_c(R=0)=30$ K. This is consistent with the Ginzburg–Landau theory for thin superconducting films near T_c. Moreover, the $I-V$ curves of these shorts are rounded, which indicates flux–flow behavior that is typical of the bare thin films. Thus, our shorts seem to be of fairly good quality,

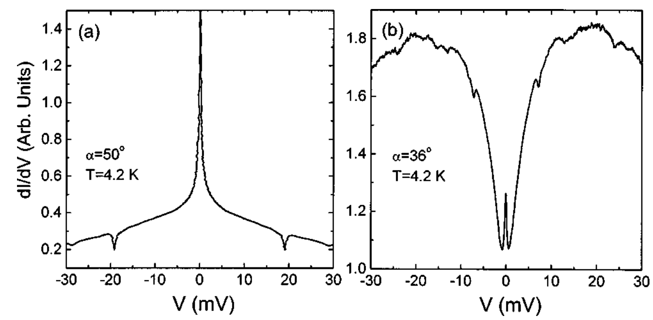

FIG. 3. Dynamic conductance (dI/dV) of oxygen-deficient YBCO/YBCFeO/YBCO edge junctions, with (a) $\alpha=50°$ and (b) $\alpha=36°$.

which allowed us to proceed and make oxygen-deficient edge junctions with the YBCFeO barriers.

These junctions were prepared with different values of the parameters d_B, d_C, d_{BAR}, d_{STEP}, and α, which are defined in inset (a) of Fig. 2. All the junctions with an edge angle of $\alpha=50°$ showed a weak-link behavior, as seen in the dynamic conductance in Fig. 3(a). Near $V=0$ one can see a zero-bias anomaly, which can be related to bound states in d-wave pairing.[9] At higher voltages, the conductance decreases with the bias voltage, which is typical of flux flow in the weak link. As opposed to this, junctions with $\alpha=36°$ showed SIS-type behavior (tunneling like), since their dynamic conductance increases with the bias voltage up to about 20 mV, as can be seen in Fig. 3(b). We, therefore, identify a crossover from weak-link to tunneling-like behavior as a function of the edge angle of the junctions. Previously, such a crossover was observed in wedge-edge junctions as a function of their oxygen content.[6] All the junctions, with the following parameters: $d_C=100$ nm, $d_B=70$ nm, $d_{\mathrm{BAR}}=20$ nm, and $d_{\mathrm{STEP}}=0$ nm had typical conductances as seen in Fig. 3. However, the resonance peaks superposed on the dynamic conductance in Fig. 3 varied from junction to junction even among the ten junctions on the same wafer.

Previously, we found ordered resonances in the cover electrode in the wedge-edge junctions.[6] To be able to detect a similar effect in the present study, we decided to increase

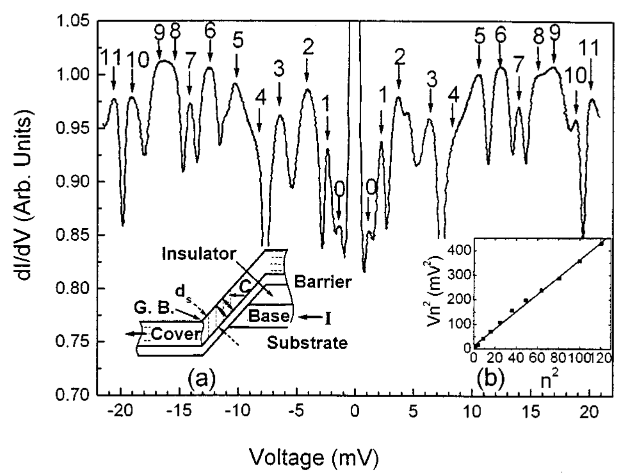

FIG. 4. Dynamic conductance (dI/dV) of an oxygen-deficient YBCO/YBCFeO/YBCO edge junction with an edge angle of $\alpha=50°$. A schematic diagram of this edge junction is shown in inset (a). In inset (b) V_n^2 of the peaks are plotted as a function of n^2.

d_{STEP}, as shown in inset (a) of Fig. 4. We thus prepared junctions with the following parameters: $d_C = 60$ nm, $d_B = 70$ nm, $d_{BAR} = 20$ nm, $d_{STEP} = 65$ nm, and $\alpha = 50°$. This yielded a series of strong resonant peaks in the conductance of all junctions, which were independent of the barrier thickness (d_{BAR}), and a typical result is shown in Fig. 4. We attribute these resonances to an interference effect in the cover electrode of quasiparticles moving perpendicular to the edge, as shown by the double arrows in inset (a) of Fig. 4. These peaks, known as Tomasch oscillations,[10] originate in Andreev scattering in which an electron-like quasiparticle is reflected as a hole-like quasiparticle from an interface of a superconductor. We fitted our results to the Tomasch oscillation formula, which is given by[11]

$$eV_n = \sqrt{(2\Delta)^2 + \left(\frac{nhv_F'}{2d_s}\right)^2}, \tag{1}$$

where Δ is the gap, v_F' is the renormalized Fermi velocity, n is the peak number, and d_s is the thickness of the superconductor (see Fig. 4). Equation (1) predicts that V_n^2 is proportional to n^2, where $n=0$ represents the peak of the gap. The graph in inset (b) of Fig. 4 shows that V_n^2 is actually proportional to n^2 for the peaks shown in the main figure. V_n was determined for each n as the average value of the positive and negative nth peaks. In three different junctions, two on one wafer with a barrier and one on another wafer without a barrier (a short), we observed a clear series of peaks, as shown in Fig. 4. From the linear fits of the measured V_n^2 to n^2, according to Eq. (1), the values of Δ and v_F' were obtained. We found Δ values in the range of 1.21–1.58 meV, and values for v_F' in the range of $(4.3–4.6)\times 10^7$ cm/s. The Δ values are close to previous measurements of a gap in the c direction where 1 and 2.4 meV were found.[6,12] The present values of the v_F' are larger by a factor of about 2 as compared to our previous results of 2.4×10^7 cm/s in the c direction,[6] but smaller than the value of 7×10^7 cm/s which was measured in the $a-b$ plane.[13] Therefore, our results are in a direction in between the c axis and the $a-b$ plane. To understand how this is possible, we note that the $I-V$ curves of our junctions showed a double transition similar to that observed by Hunt *et al.*[14] This indicates that a grain-boundary junction in series with the edge junction is formed at the lower part of the edge in the cover electrode[15] [see GB in inset (a) of Fig. 4]. As a result, the c axis of the cover electrode which faces the edge of the base electrode is *parallel* to the wafer. Thus, the measured Δ and v_F' values contain contributions from the c-axis directions as well as the $a-b$ plane. Series of equally spaced peaks in the conductivity, seemingly similar to our results, were predicted by Xu, Miller, and Ting[16] in a NINS structure where S is either a $d_{x^2-y^2}$ or an s-wave superconductor. However, they found these peaks for the (110) interface orientation, while in our case the interfaces are oriented always at the (100) direction. Moreover, the spacing between their peaks is proportional to $1/d_N$, where d_N is the thickness of the normal metal, while we find no such dependence in our results. Therefore, the resonances that we observed do not originate in the normal metal as Xu *et al.* have discussed.

In summary, we observed a crossover from weak-link to tunneling-like behavior versus the edge angle in our oxygen-deficient junctions. Strong resonant peaks were observed in the conductivity and some series of peaks were attributed to Tomasch oscillations in the cover electrode. Analysis of these series yielded $\Delta = 1.21–1.58$ meV, and $v_F' = (4.3–4.6)\times 10^7$ cm/s, which are in general agreement with previous results. Currently, we look for the scaling of these series of peaks with the thickness of the cover electrode, to further support our interpretation of these peaks as due to Tomasch oscillations.

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