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Normal electron tunneling in ramp-type $YBa_2Cu_3O_7/PrBa_2Cu_3O_7/YBa_2Cu_3O_7$ junctions prepared by laser ablation

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Ramp-type $YBa_2Cu_3O_7/PrBa_2Cu_3O_7/YBa_2Cu_3O_7$ tunneling junctions have been prepared by laser ablation. The voltage dependence of the differential conductance is measured at different temperatures and magnetic fields. The junctions are thermally stable and can be cooled down to liquid-helium temperature and warmed up again to room temperature several times without quality loss. At temperatures below 35 K they show clear indications of an energy gap and in the same temperature range a very sharp zero-bias anomaly.

I. INTRODUCTION

In the last years rapid progress has been made in the fabrication of high-T_c tunnel junctions.[1] The best results so far have been achieved on chemically etched $YBa_2Cu_3O_7$ single crystals.[2] Just recently low-leakage tunneling junctions were prepared in thin film technology using the ramp-type geometry[3] known from Josephson devices.[4] However, there is still much uncertainty about the temperature behavior of the gaplike feature of these materials. One of the main reasons for this is the lack in thermal stability of the junctions, especially in the temperature range above 40 K. Another feature that is often seen in junctions made of high-T_c material but not yet understood is the so-called zero-bias anomaly (ZBA),[5,6] i. e., a peak in the conductance at zero-bias voltage.

II. PREPARATION

The junctions are prepared by a four-step process, where an $YBa_2Cu_3O_7$ base electrode, a $LaAlO_3$ protective layer, a $PrBa_2Cu_3O_7$ barrier, and an $YBa_2Cu_3O_7$ counterelectrode are deposited consecutively on a (100)-$SrTiO_3$ substrate. The resulting structure of the edge junction is shown in Fig. 1. During the first two process steps half of the substrate is covered by a shadow mask that is made of $SrTiO_3$ so that contamination of the base electrode is minimized. In order to avoid nonstoichiometric scattering and to get a small ascent length d (see Fig. 1) the slit between the shadow mask and the substrate is only about 1 μm. With this setup an ascent length of about 5 μm is reached. The 3000 Å thick $YBa_2Cu_3O_7$ base electrode is deposited by laser ablation at 850 °C in 0.2 mbar O_2. This process was described in detail previously.[7] After changing the target a 4000 Å thick $LaAlO_3$ protective layer (surface resistance $> 40\,k\Omega/cm^2$) is prepared under the same conditions. This layer reduces the effective area of the junction and hence the probability for the formation of microshorts. As the substrate faces the target under the same angle of incidence, probably some $LaAlO_3$ is deposited on the ascent of the base electrode, thus enhancing the insulating barrier. After these preparation steps the film is cooled down to room temperature in 700 mbar O_2 and the vacuum chamber is opened in order to remove the shadow mask. Finally, the 100 Å thick $PrBa_2Cu_3O_7$ barrier and the 3000 Å thick $YBa_2Cu_3O_7$ counterelectrode are ablated under the same conditions as for the first two layers. The resistively measured transition temperatures of the $YBa_2Cu_3O_7$ electrodes range from 87 to 89 K. With a 100 Å thick $PrBa_2Cu_3O_7$ barrier other groups obtained Josephson junction behavior. In our case two facts suppress Josephson coupling: First, as mentioned above $LaAlO_3$ might be deposited also on the ascent of the base electrode. Second, Al might diffuse into the $YBa_2Cu_3O_7$ base electrode and thus even supress superconductivity.

The junctions are prepared by photolithographic patterning of 10 μm wide bridges and wet chemical etching

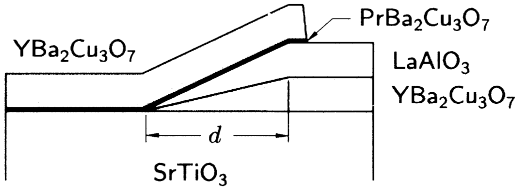

FIG. 1. Schematic drawing of the junction. The thicknesses of the different layers are exaggerated for clarity.

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with diluted phosphoric acid. Since the base electrode is protected by the $LaAlO_3$ layer only the counterelectrode and the $PrBa_2Cu_3O_7$ layer are etched. By this method the overlap region is reduced to $10 \times 15\,\mu m^2$ while the actual junction area is about $0.5 \times 10\,\mu m^2$.

III. TUNNELING MEASUREMENTS

The conductance curves were measured directly using an ac modulation technique. The amplitude of the ac signal was $200\,\mu V$ and the frequency 90 Hz. The temperature was varied between 2.1 K and 100 K and magnetic fields up to 6 T were applied.

The resistance of the device below the critical temperature of the $YBa_2Cu_3O_{7-\delta}$, measured in four-probe geometry using a constant current of $0.1\,\mu A$, is mainly governed by the resistance of the $PrBa_2Cu_3O_{7-\delta}$ layer. At T_c the junction resistance drops to about one half of the value in normal state. The *shape* of the conductance curves, however, does not change at T_c, but the curvature of the curve becomes gradually smaller with higher temperature. The change in the background conductance between 2 K and 110 K is too large to be explained by a density-of-states effect of $YBa_2Cu_3O_{7-\delta}$ as proposed by Anderson and Zou[8] or Varma[9]. Thus we conclude that it is due to the specific configuration of the junction, e. g., due to inelastic tunneling in the barrier region, as proposed by Kirtley and Scalapino.[10]

Whereas most tunneling junctions of $YBa_2Cu_3O_{7-\delta}$ show only a change in slope or a shoulder at ± 20 mV,[11,12] the observation of well-developed maxima is not as common. Using ramp-type junctions of $YBa_2Cu_3O_7/PrBa_2Cu_3O_7/YBa_2Cu_3O_7$ and $YBa_2Cu_3O_7/CeO_2/YBa_2Cu_3O_7$ we could reproducibly observe the existence of such a maximum (see Fig. 2). Between 2.1 K and 27.8 K it did not shift appreciably and the mean value of its position is 22.7 ± 0.9 mV concluded from the peak-to-peak distance of the maxima at either bias side. If superconductor-superconductor tunneling is assumed, this would lead to $2\Delta/k_BT_c = 3.0 \pm 0.1$. This value is lower than the gap along the c axis but nearly half of the value which is commonly accepted for the gap in the ab-plane.[1] This would imply that one electrode of the junction is so much degraded, that superconductor-normal conductor tunneling is observed, which is, as already mentioned, in principle possible. The model that the energy gap is reduced since the high-T_c superconductors are close to the metal-insulator transition[13] cannot explain why the peaks occur at *half* of the expected position. That the maxima vanish above 35 K might be due to the increased conductance of the $PrBa_2Cu_3O_7$ layer. If the conductance is high enough, nontunneling channels contribute significantly to the transport across the junction and all information about the superconducting state is lost.

Other maxima at about 80 mV do not seem to be intrinsic, because they could not be observed in further measurements on the same junction or other junctions.

The conductance peak at zero bias is much sharper than those widely reported in literature. It is even sharper than would be expected from thermal excitation. In Fig. 3 the standard deviation σ of the maxima as concluded from a Gaussian fit is compared with the thermal energy k_BT, i. e., the width of a thermally broadened line. At low temperatures both agree very well, but at higher temperatures the ZBA is much sharper. It might be argued that the behavior of the ZBA can be readily explained as a critical current or a Josephson current

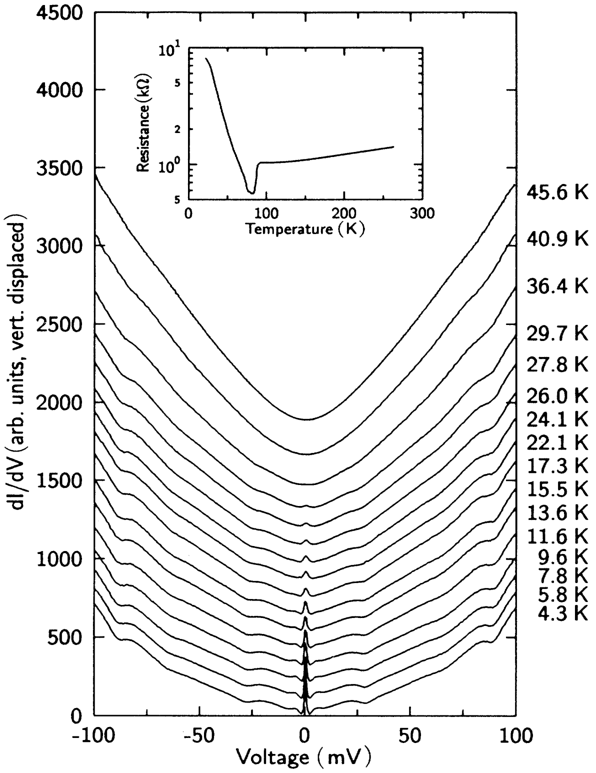

FIG. 2. Temperature dependence of the conductance curves of an $YBa_2Cu_3O_7/PrBa_2Cu_3O_7/YBa_2Cu_3O_7$ ramp-type junction. The zero refers to the bottom curve, the upper curves are shifted by 100 units, respectively. The inset shows the temperature dependence of the junction resistance measured in standard four-probe geometry using a current of $0.1\,\mu A$.

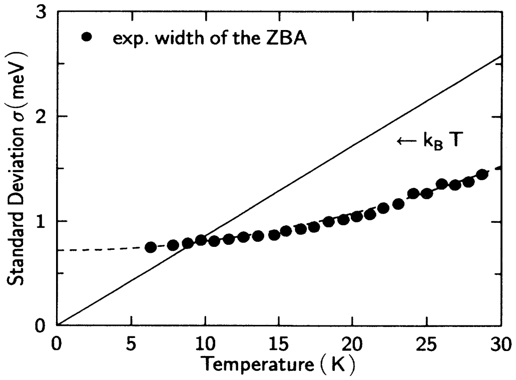

FIG. 3. Comparison of the width of the zero-bias anomaly determined by fitting a Gaussian curve and the thermal energy k_BT.

between the two electrodes. But in $V(I)$ measurements using a current source and a nanovoltmeter there is no indication of a transport critical current. The slope of the $I(V)$ curves is higher around zero bias but not infinitely high (see Fig. 4). In principle this could be explained by a Josephson current between two extremely weakly coupled superconductors that is broadened by thermal fluctuations. But an attempt to fit the $V(I)$ curves with the Ambegaokar-Halperin model[14] showed that the experimental width of the ZBA is larger than the theoretically predicted one. Moreover, in magnetic fields up to 6 T the ZBA is hardly broadened and reduced (see Fig. 5), so that Josephson currents can be ruled out as a cause of the ZBA. If the ZBA was due to a supercurrent, it should be enhanced by increasing the conductance of the $PrBa_2Cu_3O_7$. But the ZBA disappears at 35 K, i. e., at the same temperature as the maxima at 20 mV. Furthermore, the cause of the observed ZBA seems to be different from that of the ZBA reported by Lesueur *et al.*,[6] since they see a strong effect of the magnetic field on the ZBA and a depression of the conductance at zero bias with increasing magnetic field.

The model of S-N layered superconductors[15–17] may explain our data in principle. It assumes that the superconductor consists of alternating superconducting and normal conducting layers. The tunneling conductance is proportional to the sum of the superconducting and normal conducting density of states weighted by the effective electronic masses

$$dI/dU \propto \frac{2}{\pi^2}\left[m_N\rho_N(E) + m_S\rho_S(E)\right]. \qquad (1)$$

This yields a nonvanishing conductance in the energy gap and a narrow maximum at zero bias. If a small coupling between the superconducting and the normal conducting layers is assumed, the gap in the c direction would obey the BCS relation $2\Delta/k_BT_c = 3.5$. In the framework of this model the zero-bias conductance peak is due to the hopping of electrons between superconducting and normal conducting layers. Since this electron exchange should not be strongly affected by magnetic fields, our observation that the ZBA is hardly broadened in magnetic fields would find a natural explanation. That the peaks in our measurements occur at about $3\frac{k_BT_c}{2}$ would be interpreted as the energy gap in the c direction, that is reduced at the surface.

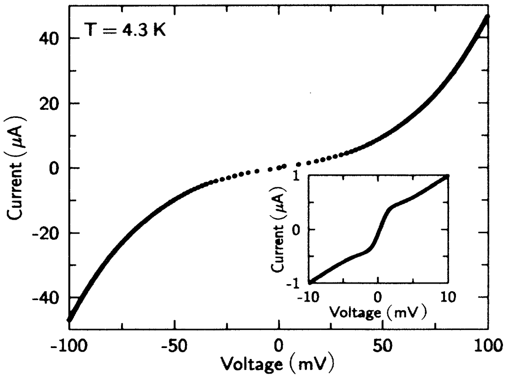

FIG. 4. $I(V)$ curve of the junction around zero bias recorded with a current source and a nanovoltmeter.

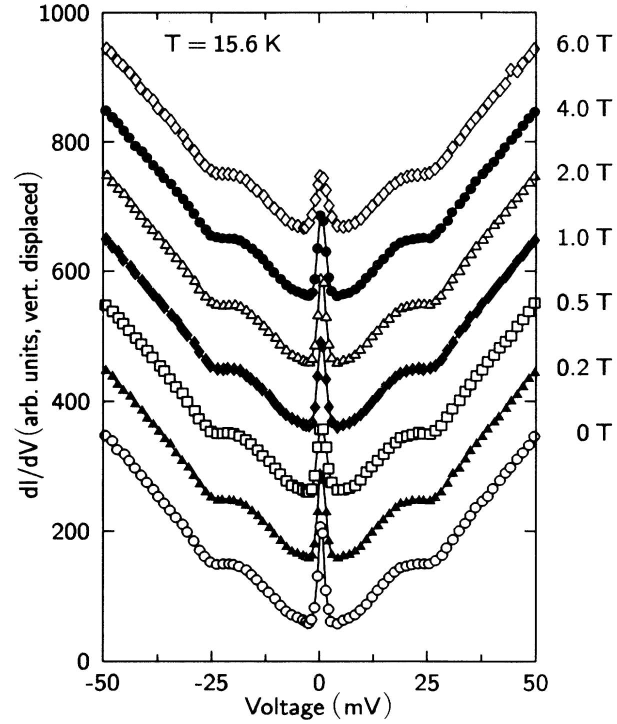

FIG. 5. Magnetic field dependence of the conductance curves (upper curves are shifted by 50 units, respectively).

IV. CONCLUSIONS

Normal electron tunneling junctions have been prepared by laser ablation of all perovskite material. The conductance curves show well developed maxima at 22.7 ± 0.9 mV, i. e., at half the value that would be expected from the reports of other groups for ab-plane tunneling between two $YBa_2Cu_3O_7$ electrodes. Besides, a zero-bias anomaly is observed that is sharper and whose magnetic field dependence is less than that of any other ZBA reported so far. Nevertheless in $V(I)$ measurements there is no indication of a supercurrent flowing across the junction. Second, the ZBA vanishes with the maxima indicative of the energy gap at around 35 K, i. e., well below the superconducting critical temperature of 88 K. This behavior would find a simple explanation if one assumes that the resistance of the insulating layer drops with increasing temperature far enough that nontunneling channels contribute significantly to the transport mechanism across the junction. The observed anomalous features in the differential conductance might be explained in the model of S-N layered superconductors.

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