Pis'ma v ZhETF, vol. 73, iss. 3, pp. 159 – 162

Superconducting energy gap in $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi2223) single crystals

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Submitted 28 December 2000

Current-voltage characteristics of $S{-}I{-}S$ tunnel break junctions fabricated from pure undoped Bi2223 single crystals ($T_c = 110$ K) have been measured. High quality of the crystals enables to produce the good tunnel junctions with a low or almost zero leakage current and well developed the gap structure in the tunneling spectra. Values of the peak-to-peak energy gap $2\Delta_{p-p}$ in different crystals and tunnel junctions ranged from 80 to 105 meV. The tunneling conductance in superconducting state was normalized by that in normal state and compared to a smeared BCS density of states. Simple fit of the data gave average value of the $\Delta = 38.5$ meV and reduced gap $2\Delta/kT_c \simeq 8$, consistent with a very strong coupling mechanism.

PACS: 74.50.+r, 74.72.Hs

An investigation of the tunneling conductance is very important for the understanding of the mechanism of superconductivity in the high-T_c superconductors. Tunneling spectroscopy was very successful to studying of a superconducting state in conventional superconductors. However, a rich variety of peculiarities observed in the tunneling spectra of the high-T_c superconductors prevent the analyzing of the experimental results uniquely. It seems likely that the most part of these unusual tunneling data can be connected with the inferior quality of the studied tunneling junctions. The shape of the current-voltage ($I - V$) characteristics are far from the ideal that for the conventional superconductors and the tunneling junctions, as a rule, do not meet the well-known requirements for the junction selection. In particular, there are scarcely any $I - V$ characteristics satisfied the Ohm's law at voltage above the superconducting energy gap. In additional, the single crystals of the layered high-T_c superconductors every so often contain a large number of very thin interlayers of the another phases. At present more reproducible results were obtained for the bilayered cuprate $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) only. Up to now, there is no definiteness in the doping level dependence of the superconducting energy gap 2Δ and $2\Delta/kT_c$ ratio [1, 2]. In this connection, it is important to measure gap value in the higher-T_c phase Bi2223 since the problem of oxygen deficiency is less dramatic in the Bi-compounds. For lack of the single crystals, the data on 2Δ in Bi2223 have been very limited. The low temperature gap values were only measured on ceramic samples with a mixture of Bi2212 and Bi2223 phases [3 – 5]. The exception is the STM experiments [6] where c-axis-oriented Bi2223 polycrystals were used.

In operation our previous tunneling studies of the high-T_c and low-T_c Bi-family superconductors [7, 8], we present here first results on the tunneling measurements in several pure undoped Bi2223 single crystals by using a break-junction technique. The high quality of Bi2223 samples enables to fabricate the good tunnel junctions with a low or almost zero leakage current and well developed the gap structure in the tunneling spectra.

$Bi_{2.11}Sr_{2.02}Ca_{1.75}Cu_{2.8}O_{10+\delta}$ single crystals with T_c(midpoint)= 110 K and $\Delta T_c = 2.5$ K (10% – 90% transition points) were obtained by free growth in gas cavities formed in KCl-solution-melt [9]. The crystals had a platelet-like rectangular shape and mirror surfaces. The sizes of the crystals were around $1 \times 1 \times 0.003$ mm. The quality of the crystals was verified by the measurements of the *dc* resistance, *ac* susceptibility, X-ray diffraction and scanning electron microscopy. It should be noted that the onset temperature of superconducting transitions and the transition widths for *dc*-resistance and *ac* susceptibility were very close. Composition of the crystals was studied in Laboratory of Solid State Physics, University of Groningen, The Netherlands. The X-ray studies showed that studied here crystals contained less than 3% of the Bi2212 phase as indicated by slightly increased width of certain reflections in the diffraction patterns [9]. The unit cell parameters were equal to $a = 5.38$ Å and $c = 36.95$ Å. Details of break-junction preparation are described by us elsewhere [7].

In Fig.1a we plotted the $I - V$ characteristics of the tunnel break junctions at $T = 4.2$ K fabricated from three Bi2223 single crystals. The curves are reproducible and reveal the characteristic features for a superconducting tunnel junction with a flat region

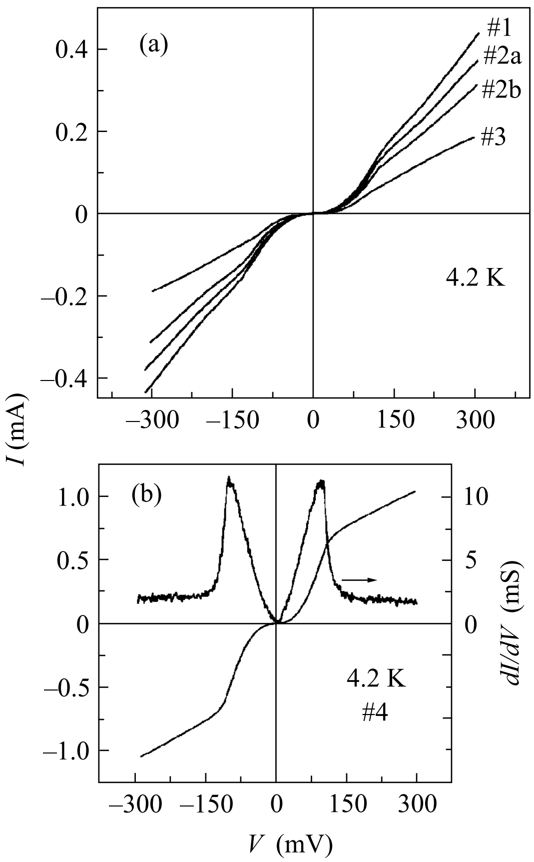

Fig.1. (a) $I-V$ characteristics of the tunnel break-junctions at 4.2 K fabricated from the three Bi2223 single crystals. (b) The representative $I-V$ and dI/dV vs V characteristics for low-resistance tunnel junction. The inferior quality of the tunneling barrier leads to considerable distortion of the curves

around zero bias voltage and a well-defined sharp increase in the tunnel current around $V = \pm(90-100)$ mV connected with a superconducting energy gap. At $|V| > |100|$ mV the $I-V$ characteristics are linear and located in line with zeroth point as it must be for the good tunnel junctions.

It is known that the break-junction technique allows to control the junction resistance and change the shape of the $I-V$ characteristics. The Fig.1b shows the representative $I-V$ curve along with the tunneling conductance data dI/dV vs V for low-resistance tunnel junction which are of frequent occurrence in experiments with high-T_c superconductors. The inferior quality of the tunneling barrier leads to considerable distortion of the $I-V$ and $dI/dV(V)$ curves. For junctions of this type even Ohm's law does not hold. Although the gap feature in this curve is more pronounced than in the classical curves, that is strongly changed and these curves are unusable for a tunneling density of states determination.

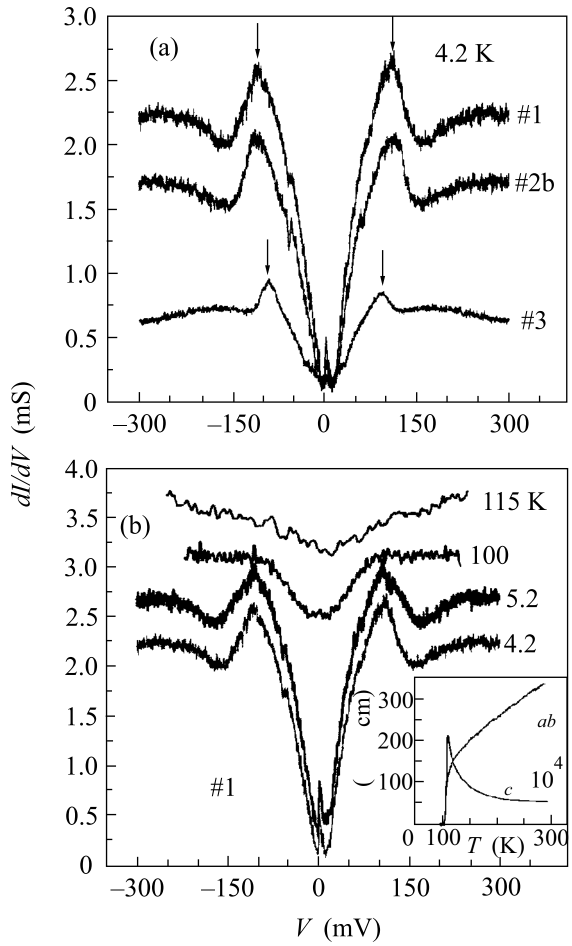

Fig.2. (a) The tunneling condactance data dI/dV vs V measured on the three crystals at 4.2 K. The arrows marked the peak positions to determine the superconducting energy gap value $2\Delta_{p-p}$. (b) The tunneling conductance dI/dV vs V at selected temperatures for one of single crystals (#1). The curves have been shifted vertically with respect to the 4.2 K curve, for clarity. The inset shows the temperature dependences in-plane and out-of-plane resistivities measured on the same crystals

Fig.2a shows the tunneling conductance data dI/dV (V) measured on three crystals at $T = 4.2$ K. The shapes of the $dI/dV(V)$ curves are very similar those for the tunneling conductance of Bi2212 [7] which were compatible with a smeared BCS density of states. For studied here $S{-}I{-}S$ junctions, the peak-to-peak distance between the two main maxima (marked by arrows) on the $dI/dV(V)$ curves corresponds to $4\Delta_{p-p}$. The values of the obtained energy gap $2\Delta_{p-p}$ in different crystals and tunnel junctions ranged from 80 to 105 meV. It should be noted that the data in Fig.2a correspond to tunnel junctions with the minimal and maximal values of $2\Delta_{p-p}$. The sharp peak in the low-temperature conductances at zero-bias voltage as in the case of Bi2212 results from the Josephson current. It has been previously shown by us [7] that this peak can be suppressed by a magnetic field.

To determine the relation between Δ and T_c, we measured the tunneling conductance $dI/dV(V)$ at selected temperatures on one of single crystals (#1). The results are shown in Fig.2b. For clarity, the curves have been shifted relative to the lower curve. In the inset, we are shown the temperature dependencies of the in-plane and out-of-plane resistivities measured on the same crystal. One can see that the gap structure broadens and diminishes at increasing temperature. Since T_c for given sample was equal 110 K, and the gap structure vanished completely at a temperature close to T_c, we can infer that the observed energy gap is surely the superconducting state gap of Bi2223.

In order to find out a relation between Δ and T_c, we normalized the smoothed conductance $dI/dV(V)_S$ of the junction in the superconducting state at 5.2 K by the smoothed conductance $dI/dV(V)_N$ in the normal state at 115 K which are displayed in Fig.3a. Thereafter we made a least-squares fit of the expression

$$dI/dV(V)_S/dI/dV(V)_N = = \frac{d}{deV}\int_0^{eV} N(E)N(E-eV)dE \quad (1)$$

to the normalized tunneling conductance, where $N(E)$ =Re$[(E-i\Gamma)/\sqrt{(E-i\Gamma)^2-\Delta^2}]$ is a smeared BCS density of states. Here Γ is a measure of the quasiparticle scattering rate [10]. The modified BCS curve (dashed line in Fig.3b) indicate that a reasonable fit of the gap region of the $T = 5.2$ K data is achieved with $\Delta = 44$ meV and $\Gamma = 21.5$ meV , except for a small region near zero, where the Josephson effect influences the measurements and the strong dips at ± 170 mV, that has been observed in many other tunnelling studies of Bi2212 single crystals. In recent tunneling experiments by DeWilde et al. [2] suggested that this dip feature in the conductance is due to a strong-coupling effect in d-wave superconductors and it arises from a frequency dependence of an electron-electron pairing interaction. The fit the data with minimal value of Δ for crystal #3 gave values $\Delta = 33$ meV and $\Gamma = 15$ meV. The obtained average value of the $\Delta = 38.5$ meV agrees closely with the earlier measurements of the energy gap on c-axis-oriented Bi2223 polycrystals [6] where $\Delta = 38$ meV was obtained. The values of the ratio

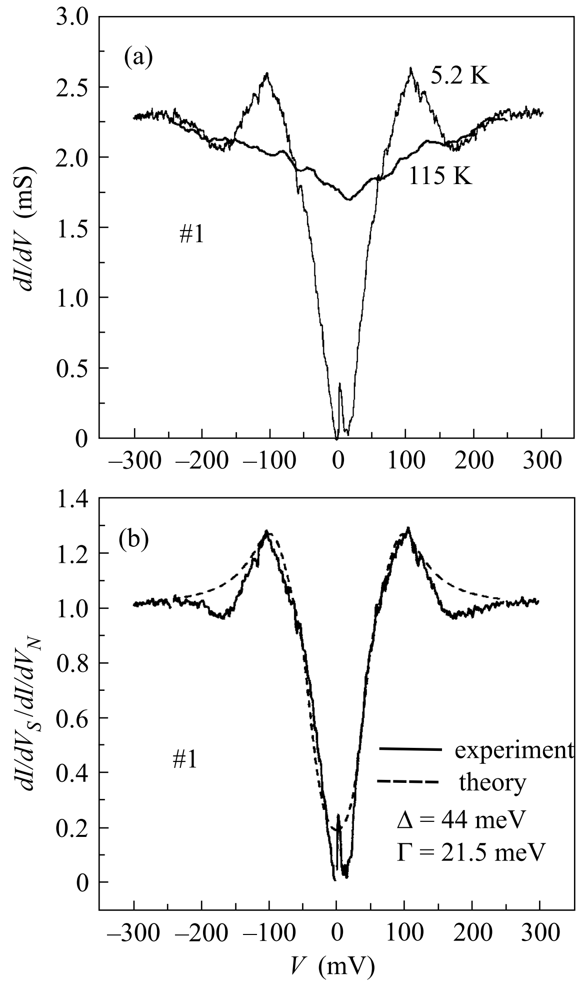

Fig.3. (a) Smoothed tunneling conductances in superconducting $(dI/dV)_S$ ($T = 5.2$ K) and normal $(dI/dV)_N$ ($T = 115$ K) states. (b) Normalized tunneling condactance $(dI/dV)_S/(dI/dV)_N$ at $T = 5.2$ K (solid line) compared with the broadened BCS density of states (dashed line)

$2\Delta/kT_c$ for our two crystals #1 and #3 are 9.2 and 7 respectively. The average value of the reduced gap $2\Delta/kT_c \simeq 8$ corresponds to a very strong coupling mechanism.

In a recent tunneling study [1] of Bi2212 single crystals with various oxygen concentrations a strong dependence of the energy gap 2Δ on oxygen doping was observed. By measuring the normal-state Hall coefficient in our crystals we have found that the concentration of the carriers n in samples is near $4\cdot 10^{21}$ cm^{-3}. Once the values of T_c and n in our single crystals are closely matched by those in the optimaly doped (Bi,Pb)2223 ceramic samples [11], one can believe that the found here magnitudes of 2Δ and $2\Delta/kT_c$ are related to the optimaly doped crystals.

We would like to thank V.P.Martovitskii for the careful X-ray studies of the single crystals. This work was supported by the Russian Ministry of Science and Technical Policy within the Program "Actual Problems of Condensed Matter Physics" (grant # 96001), and by the Russian Foundation for Basic Research (grant # 99-02-17877).

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