Point-contact and tunneling spectroscopy of $YBa_2Cu_3O_{7-x}$ and $YbBa_2Cu_3O_{7-x}$ (90-K phase) single crystals

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Point-contact and tunneling spectroscopy has been used to determine the gap parameter Δ of single crystals of $YBa_2Cu_3O_{7-x}$ [$28\ \mathrm{meV} \leqslant \Delta\ (4.2\ \mathrm{K}) \leqslant 33\ \mathrm{meV}$] and $YbBa_2Cu_3O_{7-x}$ [$29\ \mathrm{meV} \leqslant \Delta\ (4.2\ \mathrm{K}) \leqslant 32\ \mathrm{meV}$], with transition temperatures $87 \leqslant T_c \leqslant 90$ K. An additional fine structure has been observed on the current–voltage characteristics of point contacts containing a subharmonic structure [$V_n = 2\Delta/(en)$]. This additional structure may stem from a quantum size effect in the quasiparticle spectrum in the N transition region of the S–N–S point contact. Current–voltage characteristics with a small excess current in the subgap region have been observed for S–I–S tunnel junctions. The shape of the current–voltage characteristics of the S–I–S contacts can be described well by the semiempirical Dynes model. A ratio $\Gamma/\Delta = 0.07$, where Γ is a smearing parameter ($T = 4.2$ K), has been found. This is a record-low value for high-T_c superconducting tunnel junctions. © *1994 American Institute of Physics.*

The subharmonic structure on the current–voltage characteristics of S–N –S point contacts, caused by multiple Andreev reflections at the S–N junctions,[1–5] yields a fairly accurate value of the gap parameter Δ of the superconductor.[6,7] In principle, detailed studies of the fine structure on the current–voltage characteristics of S –N–S point contacts at subgap bias voltages offer interesting possibilities for studying the physical nature of superconductivity.[8,9] This is a timely opportunity for the high-T_c superconducting materials. The experimental results available on the current–voltage characteristics of high-T_c superconducting point contacts of the S–N–S type based on $YBa_2Cu_3O_{7-x}$ (Refs. 10 and 11) at $T = 4.2$ K reveal several characteristic dips in the differential conductance (dI/dV), at bias voltages which satisfy the relation[2–5] $V_n = 2\Delta/(en)$. The structural features which have been observed indicate that there is a sharp gap boundary at $T \ll T_c$ in $YBa_2Cu_3O_{7-x}$. In the case of S–I –S tunnel junctions, this sharp boundary

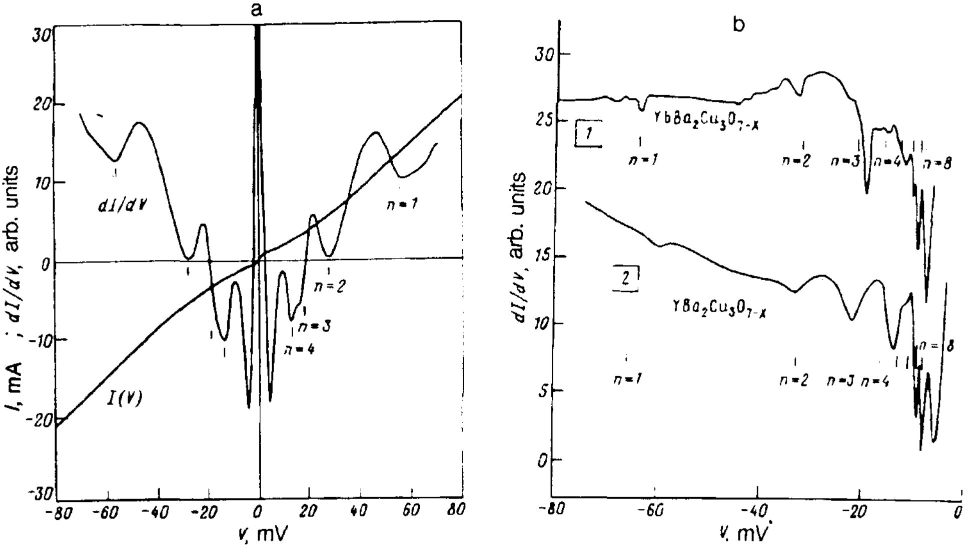

FIG. 1. a: $I(V)$ and $dI(V)/dV$ characteristics of a point contact based on a $YBa_2Cu_3O_{7-x}$ single crystal (sample WE-2, $T_c = 90$ K) at $T = 4.2$ K. The line segments mark the voltages $V_n = 2\Delta/(en)$, at which dips are expected to arise in the dynamic conductance ($\Delta = 28$ meV). b: $dI(V)/dV$ characteristics of point contacts based on several single crystals. 1—$YbBa_2Cu_3O_{7-x}$ [sample WIN-21M, $T_c = 87$ K, $\Delta(0) = 32$ meV]; 2—$YBa_2Cu_3O_{7-x}$ [sample WOLF-1B, $T_c = 87$ K, $\Delta(0) = 33$ meV] at $T = 4.2$ K. The line segments have the same meaning as in part a.

should be manifested in a small excess current at subgap voltages and also in a well-defined gap feature on the current–voltage characteristic at $V_g = 2\Delta/e$.

The published values of the gap parameter Δ at $T = 4.2$ K for $YBa_2 Cu_3O_{7-x}$ (the "90-K phase"), found from data from point-contact measurements on S–N–S contacts[10,11] and N–S contacts,[12–14] lie on the interval from (on the one hand) 29–30 meV (Refs. 12 and 10) to (on the other) 20–24 meV (Refs. 13 and 11). One possible reason for the substantial scatter in the values of Δ is an unsatisfactory surface state of the high-T_c superconducting material.[14] It seemed worthwhile to measure the gap parameter on S–N–S point contacts based on $YBa_2Cu_3O_{7-x}$ single crystals of good quality with the help of cryogenic cleaved surfaces (break junctions) and to compare the results with data from tunneling measurements on the same crystals. By adjusting the contact at a break junction, one can "tune" from the point-contact regime to the tunneling regime in a comparatively easy way.[7,10]

In this letter we are reporting measurements of the current–voltage characteristics of break junctions[15] in single crystals of $YBa_2Cu_3O_{7-x}$ and $YbBa_2Cu_3O_{7-x}$ (the 90-K phase), with transition temperatures $87 \leqslant T_c \leqslant 90$ K, in the point-contact and tunneling regimes, at $T = 4.2$ K. The superconducting transition temperature T_c was found from the temperature dependence of the resistance, $R(T)$, which was measured just before the formation of the break junction in the single-crystal sample at liquid-helium temperature [the T_c's of the $YbBa_2Cu_3O_{7-x}$ samples were also found from the temperature depen-

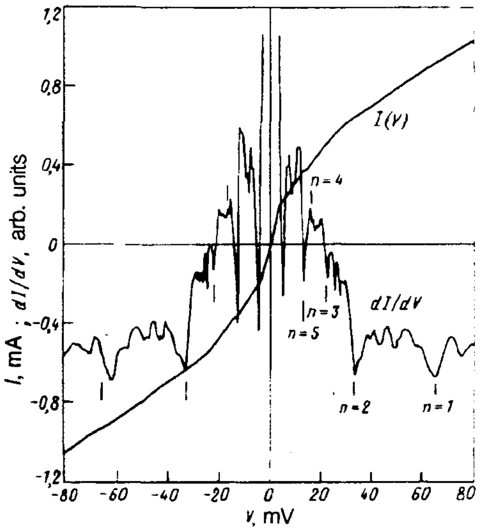

FIG. 2. $I(V)$ and $dI(V)/dV$ characteristics of a point contact based on a $YBa_2Cu_3O_{7-x}$ single crystal (sample WOLF-1D, $T_c=87$ K) at $T=4.2$ K. The line segments mark the voltages $V_n=2\Delta/(en)$ ($\Delta=33$ meV).

dence of the magnetic susceptibility, $\chi(T)$]. The transition width ΔT was 1–2 K in most cases. To quickly record a current–voltage characteristic during tuning of the contact we used an oscilloscope attachment which made it possible to reliably monitor the transition of the contact from the tunneling regime to the point-contact regime and back. A computer-controlled bridge circuit was used to measure the $I(V)$ and $dI(V)/dV$ characteristics of the break junction.

At liquid-helium temperature, we observed a reproducible subharmonic structure (Fig. 1, a and b, and Fig. 2) on the current–voltage characteristics of break junctions in $YBa_2Cu_3O_{7-x}$ and $YbBa_2Cu_3O_{7-x}$ single crystals. This structure consisted of a series of sharp dips in the dynamic conductance dI/dV, at bias voltages V_n which satisfy the condition $V_n=2\Delta/(en)$ quite accurately.[2-5,16] The current in the sample contacts was usually oriented in the ab plane, so the values of the gap parameter reported below should be associated with Δ_{ab}.

Table I shows the values which we found for $V_n(T=4.2\text{ K})$ for the $YBa_2Cu_3O_{7-x}$ and $YbBa_2Cu_3O_{7-x}$ samples (data from Ref. 10 are shown for comparison). Analysis of the subharmonic structure on the current–voltage characteristics of the point contacts found in the present study leads to the following conclusions: 1) The large number of dips (up to eight or nine) in the dynamic conductance on the $dI(V)/dV$ characteristics and the clear definition of these dips indicate that there is a sharp gap boundary in the bulk quasiparticle spectrum of these $YBa_2Cu_3O_{7-x}$ and $YbBa_2Cu_3O_{7-x}$ single crystals (at liquid-helium temperature, at least). 2) The values found for the gap in the point-contact measurements (Δ_{pc}) and the tunneling measurements (Δ_{tun}) in the present study agree well. This agreement supports the interpretation of the structure observed on the current–voltage characteristics of the point contacts (Figs. 1 and 2). 3) The values found for the ratio $2\Delta(0)/(kT_c)$ for the single crystals of $YBa_2Cu_3O_{7-x}$ and $YbBa_2Cu_3O_{7-x}$ (the 90-K phase[17]) lie in the interval $7\leqslant 2\Delta(0)/kT_c\leqslant 9$.

TABLE I. Values of the voltage V_n corresponding to minima of the dynamic conductance of a point contact, $dI(V)/dV$, at $T=4.2$ K for the $YBa_2Cu_3O_{7-x}$ and $YbBa_2Cu_3O_{7-x}$ single crystals, along with corresponding data on $YBa_2Cu_3O_{7-x}$ from Ref. 10. Shown in parentheses are results calculated from the formula $V_n=2\Delta_{pc}/(en)$, where Δ_{pc} is the gap determined in the point-contact regime. Also shown here are values of the gap Δ_{tun}, determined in the tunneling regime.

Test sample	V_1, mV	V_2, mV	V_3, mV	V_4, mV	V_5, mV	V_6, mV	V_7, mV	V_8, meV
$YbBa_2Cu_3O_{7-x}$	±64	±33.4	±19.6	±15.4	±12	±10.5	±9.4	
(sample WIN-21M)	(±64)	(±32)	(±21.3)	(±16)	(±12.8)	(±10.7)	(±9.1)	(±8)
Δ_{pc} = 32 meV								
Δ_{tun} = 29.8 meV								
T_c = 87 K								
$YBa_2Cu_3O_{7-x}$	±65	±33.7	±22.5	±16.5	±13.2		±9.5	±8.4
(sample WOLF-1D)	(±66)	(±33)	(±22)	(±16.5)	(±13.2)	(±11)	(±9.4)	(±8.25)
Δ_{pc} = 33 meV								
Δ_{tun} = 32 meV								
T_c = 87 K								
$YbBa_2Cu_3O_{7-x}$	±59.8	±33.5	±22.1		±13.8	±11.5	±9.3	±8.2
(sample WOLF-1B)	(±66)	(±33)	(±22)	(±16.5)	(±13.2)	(±11)	(±9.4)	(±8.25)
Δ_{pc} = 33 meV								
Δ_{tun} = 34 meV								
T_c = 87 K								
$YBa_2Cu_3O_{7-x}$	±56.7	±28	±17.2	±13.5				
(sample WE-2)	(±56)	(±28)	(±18.7)	(±14)				
Δ_{pc} = 28 meV								
Δ_{tun} = 26 meV								
T_c = 90 K								
$YBa_2Cu_3O_{7-x}$	±(60–70)	±27.5	±19	±12				
Ref. 10	(±56)	(±28)	(±18.7)	(±14)				
Δ_{pc} = 28 meV								

Note that the amplitude of the dip with $n=1$ in the dynamic conductance dI/dV often turns out to be very small, and the position of the dip is shifted slightly from the expected value $V_1=2\Delta/e$, in the direction of lower voltages (Fig. 1b). The evident reason is a heating of the point contact at high voltages.[6,18]

In several cases we observed an additional fine structure on the point-contact characteristics. This fine structure is seen most clearly on the $dI(V)/dV$ characteristic in Fig. 2. The structure is probably due to a quantum-size effect in the quasiparticle spectrum in the N region of the point contact, between the superconducting banks.[8]

The comparative ease with which the break junctions go into the point-contact regime is characteristic of all high-T_c superconducting materials.[19] This circumstance poses some major difficulties in efforts to find purely tunneling characteristics (the onset of a significant excess current at nonideal S–I–S contacts as the result of Andreev reflection was discussed in Ref. 20). In several cases we were nevertheless successful in obtaining current–voltage characteristics of break junctions in the tunneling regime in

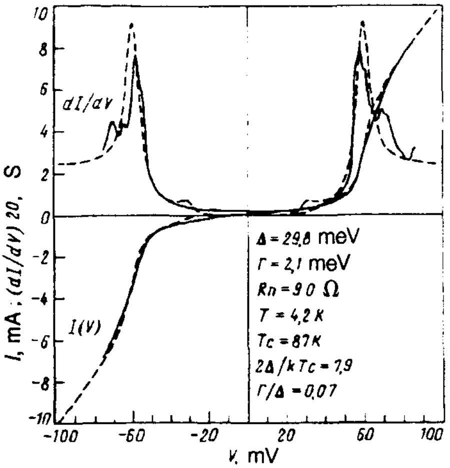

FIG. 3. $I(V)$ and $dI(V)/dV$ characteristics of a break junction in a $YbBa_2Cu_3O_{7-x}$ single crystal (sample WIN-11, $T_c=87$ K) at $T=4.2$ K. Solid curves—Experimental; dashed curves—results calculated for an $S-I-S$ contact on the basis of the Dynes model ($\Delta=29.8$ meV, $\Gamma=2.1$ meV, $R_n=9$ Ω, $2\Delta/kT_c=7.9$, $\Gamma/\Delta=0.07$).

high-quality $YbBa_2Cu_3O_{7-x}$ crystals. The characteristics had small excess currents and a shape which can be described in general features by the standard Dynes model[21] and which is approximately (in a qualitative sense) the same as that of the current–voltage characteristics of $S-I-S$ contacts based on classical superconductors[22] (Fig. 3).

Calculations show (see the dashed curves in Fig. 3) that the size of the gap parameter $\Delta(4.2\ \text{K})$ agrees well with the results of the point-contact measurements (Table I) and that the ratio of the smearing parameter Γ to the gap size Δ reaches a record low value: $\Gamma/\Delta=0.07$ ($T=4.2$ K).

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