Tunneling microscopy of a cleaved $YBa_2Cu_3O_{7-\sigma}$ single crystal at 4.2 K

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A scanning tunneling microscope has been designed and constructed for cleaving a sample and carrying out measurements at liquid-helium temperature. Scanning tunneling micrographs of a cleaved surface of an $YBa_2Cu_3O_{7-\sigma}$ single crystal in its superconducting state have been obtained. The value found for Δ from the tunneling current-voltage characteristics decreases with decreasing distance between the needle tip and the sample.

One factor which prevents the attainment of a high spatial resolution in scanning tunneling microscopy[1] (STM) of the crystallographic and electronic structures of the surfaces of high-temperature superconductors is the presence of a relatively thick insulating layer (100 Å) on the surface (Refs. 2 and 3, for example). There are obviously disadvantages in using STM to measure current-voltage characteristics of high-temperature superconductors when the needle tip must pierce the insulating surface layer in order to operate properly.

Scanning tunneling micrographs of high-temperature superconductors with a high spatial resolution (down to the atomic size) have been obtained[4] on cleaved samples of ceramic$YBa_2Cu_3O_{7-\sigma}$. The cleavage was carried out at atmospheric pressure, and then the sample was placed in a vacuum chamber (with a pressure of 10^{-6} Torr). The measurements were carried out at room temperature.

In the present study we have prepared a stable and atomically clean surface of a high-temperature superconductor by cleaving a single crystal at liquid-helium temperature. We used the scanning tunneling microscope of Ref. 5, modified for operation at low temperatures, to study the surface relief and current-voltage characteristics of a cleaved $YBa_2Cu_3O_{7-\sigma}$ single crystal.

The crystals were wafers with characteristic dimensions of $1\times1\times0.2$ mm. The **C** vector (the [001] direction) was perpendicular to the plane of the wafer. According to measurements of the magnetic susceptibility of the samples, the superconducting transition temperature was 90 K, and the width of the transition was ≈ 2 K. The crystal to be cleaved was immersed in liquid helium. The cleavage technique can be outlined as follows. The large-area faces of a sample were cemented to two plane metal surfaces, which constituted a "substrate" and a "lever." When a force was applied to the lever through an appropriate drive, the lever separated from the substrate, taking part of the sample with it. The needle of the scanning tunneling microscope was then brought up to within ~ 5 mm of the cleaved surface. The needle was a mechanically sharpened piece of Pt-Ir wire 0.3 mm in diameter. The cleaved surface usually contained some plane mirror-finish regions of significant size.

Measurements of low-energy electron diffraction, Auger spectra, and the characteristic electron energy-loss spectra of the cleaved samples, carried out by the same method, at room temperature in ultrahigh vacuum, revealed the following. 1. A significant fraction of the cleaved surface is an atomically clean (001) face, which produces an intense diffraction pattern. The typical size of the plane regions, found from the width of the diffraction reflections, is greater than 100 Å. 2. There is a pronounced deficiency of oxygen in the surface layer.

Figure 1 shows an STM image of the relief of a cleaved surface, recorded by applying a voltage of 200 mV between the needle tip and the sample and passing a tunneling current of 1 nA. The quality of the STM images differs from region to region. On the image we can clearly see flat parts of the surface, oriented parallel to (001) planes.

Figure 2 shows current-voltage characteristics and their derivatives, measured at a common point on a sample for various widths of the tunneling barrier. The current-voltage characteristics were recorded in the following way. In a regime of imaging the surface profile, the needle was stopped at the point of interest, the feedback was disconnected for a few seconds, and the voltage across the tunnel junction was varied over a given interval. The value of Δ was found as half the distance between the maxima closest to the zero voltage on the $\partial I/\partial U(U)$ curve. We see from Fig. 2 that Δ

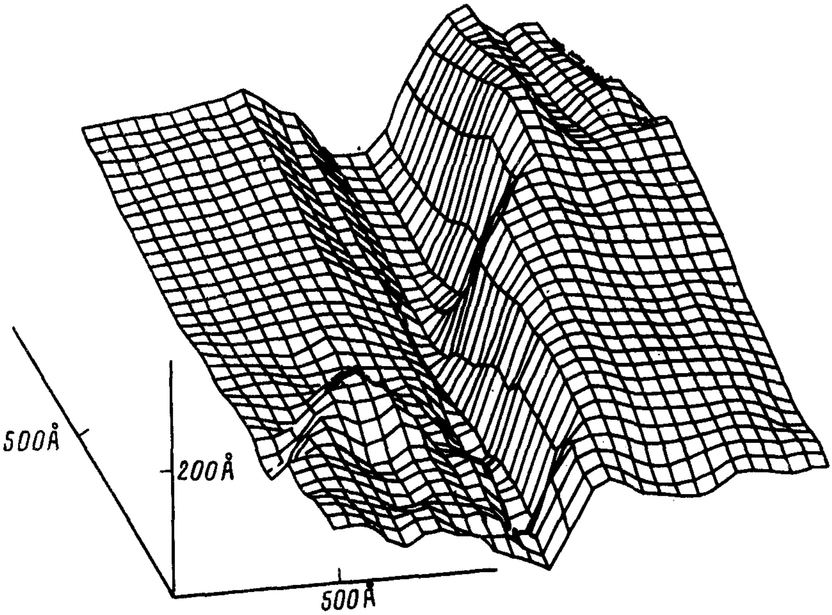

FIG. 1. Image of a cleaved surface obtained by scanning tunneling microscopy. The voltage between the needle and the sample was 200 mV, and the tunneling current was 1 nA.

depends on the width of the tunneling barrier. For the current-voltage characteristics shown in Fig. 2, the change in Δ is $\approx 30\%$. The greatest change found was nearly 100%. In all cases, the value of Δ decreased with decreasing width of the tunneling barrier.

Current-voltage characteristics were recorded at several points along a line seg-

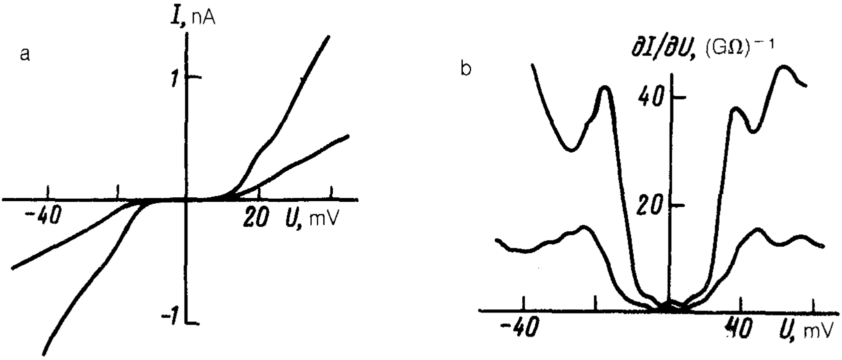

FIG. 2. a—Current-voltage characteristics of a tunneling junction at the same surface point for different widths of the tunneling barrier; b—derivatives of the I-V characteristics in Fig. 2a.

ment 4000 Å long. The characteristics varied from point to point; in particular, the value of Δ and the ratio $[\partial I/\partial U(U=\Delta)/\partial I/\partial U(U=0)]$ varied. The values of Δ lie in the interval 18–34 mV, which corresponds to $4.6 \leqslant 2\Delta/kT_c \leqslant 8.7$.

In summary, we have recorded STM images of a cleaved surface of a single crystal of $YBa_2Cu_3O_{7-\sigma}$ at 4.2 K. We have found the behavior of Δ, determined from the current-voltage characteristics, as a function of the width of the tunneling barrier for a fixed surface region. The reasons for the observed dependence may be a proximity effect and a crystallographic anisotropy of Δ. It is possible that these factors are responsible for the wide range of Δ values which have been found by the method of tunneling spectroscopy.

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