Detection of the proximity effect in Au/YBCO bilayers at 77 K with the aid of a low-temperature scanning tunneling microscope

V. V. Khanin, D. V. Shuvaev, O. V. Snigirev, E. S. Soldatov, A. S. Trifonov, and I. I. Vengrus
Department of Physics, Moscow State University, 119899 Moscow, Russia

M. Yu. Kupriyanov
M. V. Lomonosov Scientific-Research Instititute of Nuclear Physics, Moscow State University, 119899 Moscow, Russia

G. Yu. Shubnyĭ and A. N. Zherikhin
Scientific-Research Center for Technological Lasers, Russian Academy of Sciences, 117971 Moscow, Russia

(Submitted 30 May 1996)
Pis'ma Zh. Éksp. Teor. Fiz. **63**, No. 12, 984–988 (25 June 1996)

The characteristic features of the conductance of a tunneling contact, formed by a microscope tip and an Au/YBCO sandwich, are investigated with the aid of a scanning tunneling microscope. It is shown that there exist three types of dependences of the conductance of the structure on the applied voltage, which are distinguished by the position of the characteristic features on the voltage axis. It is established that this difference is due to the local characteristics of the proximity effect in gold films on a high-T_c superconductor surface. It is concluded that the transmittance of the YBCO/Au boundary is spatially strongly nonuniform.
[S0021-3640(96)02012-9]

PACS numbers: 74.50.+r, 74.76.Bz

Step-edge SNS Josephson structures with high-T_c superconducting electrodes are currently considered to be a promising basic elements for a whole series of cryoelectronic devices.[1–5] However, the question of the physical mechanism of current transport through the SN boundary of these structures has remained open for a long time. In the first theoretical models,[6,7] it was assumed that these boundaries are characterized by low transmission and are uniform in directions perpendicular to the lines of current. This approach made it possible to explain the experimentally observed strong suppression of the critical current of the junctions but not the form of their current–voltage characteristics (IVCs). Indeed, it followed from the theoretical results of Refs. 8 and 9 that for such low values of the transmittance of the boundaries a current deficit should be observed in the IVCs at high voltages, whereas most experiments indicated the presence of an excess current. To resolve this discrepancy, it was proposed in Refs. 10 and 11 that the SN boundary oriented in a direction perpendicular to the crystallographic c axis is spatially nonuniform as a result of the fact that the crystallographic ab planes emerge at the interface. Such a boundary can contain steps, i.e., geometrically small regions, with a much higher transmittance, through which the main current flow through the boundary occurs. In the superconductor–constriction–normal metal–superconductor (S–C–N–S) type structure formed in this manner, both the critical and excess currents are of the same order of magnitude (they are proportional to the square of the transmittance of the boundary).

Unfortunately, the correctness of this approach to describing transport through the YBCO/Au boundary has never been directly confirmed experimentally. A promising method for investigating such boundaries is the application of a scanning tunneling microscope (STM).[12] Our objective in the present work was to investigate with the aid of a STM the local characteristics of the proximity effect in gold films on a high-T_c superconductor surface (specifically, a YBCO film) at liquid-nitrogen temperature.

OBJECT OF INVESTIGATION

A YBCO film of the order of 250 nm thick was deposited on a $SrTiO_3$ substrate in a laser deposition system equipped with a KrF excimer laser operating in the standard mode. After deposition, the YBCO sample was cooled to a temperature of 90–100 °C in oxygen, the chamber was once again evacuated within several minutes, the YBCO target was replaced by a gold target, and a gold film was deposited on the sample. Next, oxygen was introduced into the chamber up to atmospheric pressure and the sample was removed.

In a number of samples, the gold film had a variable thickness. For this, a shutter was placed in the chamber, forming a partial shadow for the plume of the sputtered material. The natural blurring of the boundary between the shadowed and unshadowed regions gave rise to a transitional section, small displacements of the STM scanning field, within which charge transport could be investigated for different thickness of the gold film.

The bilayer structures obtained were examined in a Cambridge Instruments electron microscope (the overall surface morphology was checked) and the crystalline structure of the YBCO film was checked in a Rigaku diffractometer. The $\Theta - 2\Theta$ scanning diffraction patterns showed a 1-2-3 c-oriented film with no a-oriented inclusions or impurities of other phases. The lattice parameter determined from the $00l$ reflections was equal to 11.70 Å. The superconducting transition temperature of the YBCO film was usually equal to 89–90 K with a transition width of 1 K.

The samples were then placed into the STM, and a topogram of the sample surface was obtained in the constant-current mode.[13] The typical topogram displayed in Fig. 1 demonstrates a scale of variation of the YBCO-film thickness (see the difference in the heights from the bottom to the top corner of the figure) as well as traces of granularity of the gold film with typical granule sizes of 20–40 nm (note the slight waviness of the surface from left to right in the figure).

MEASUREMENT PROEDURE AND RESULTS

The local characteristic of the proximity effect—the effective gap in the density of states—was determined from the conductance spectra obtained at 77 K with the aid of a low-temperature STM built at the Institute of Computer-Aided Design of the Russian

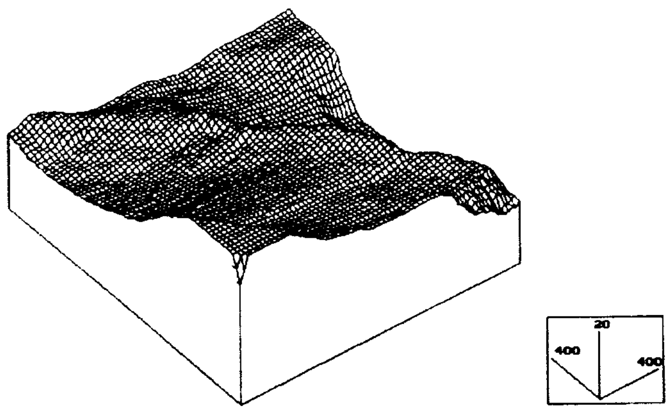

FIG. 1. Topogram of the surface of one of the experimental samples. The scale markers are in angstroms.

Academy of Sciences, St. Petersburg. This instrument possesses at $T=77$ K a resolution of ~ 3 Å in the horizontal direction and ~ 1 Å in the vertical direction and makes it possible to observe the surface over a 900×900 nm area. The tunneling resistance can be monitored in the range $10^{-5}-10^{10}$ Ω, which makes it possible to record confidently features in the IVC with a voltage resolution of approximately 0.1 mV.

The conductance spectra were measured at 49 points on an area whose dimensions could be chosen from 2×2 up to 900×900 nm. The spectra were measured by a modulation method;[13] they were not calculated by differentiating the IVC, as is very often done (see, for example, Ref. 12). This increased the accuracy of the measurements, since for the typical time of 1 ms required to measure the IVC (200–300 points), the analog differentiation noise was found to be several times weaker than the noise in digitizing and subsequent numerical differentiation of the curve.

The STM measurements showed that a stable regime of measurement of the spectra existed, as a rule, for film thicknesses greater than 15 nm.

The typical conductance spectra obtained by scanning the STM tip above the surface of the YBCO/Au sandwich are displayed in Fig. 2.

For N-layer thicknesses ($d\approx 30-50$ nm) greater than the effective coherence length and the electron mean free path length in gold, the obtained dependences are always close to the IVC of N–C′–N type junctions, where the constriction C′ was formed by the microscope tip. They had the form of parabolas with the voltage varying over a wide range from -100 mV to $+100$ mV and were approximately constant in a narrow range of voltages, which are significant for the present problem, from -20 mV to $+20$ mV. No features were registered near zero voltage within the limits of accuracy of the measurements.

For gold film thicknesses which were small but such that the film was now definitely continuous ($d=20-30$ nm), three types of spectra were observed by scanning the surface (see Fig. 2). The first and most often encountered class of IVCs is qualitatively

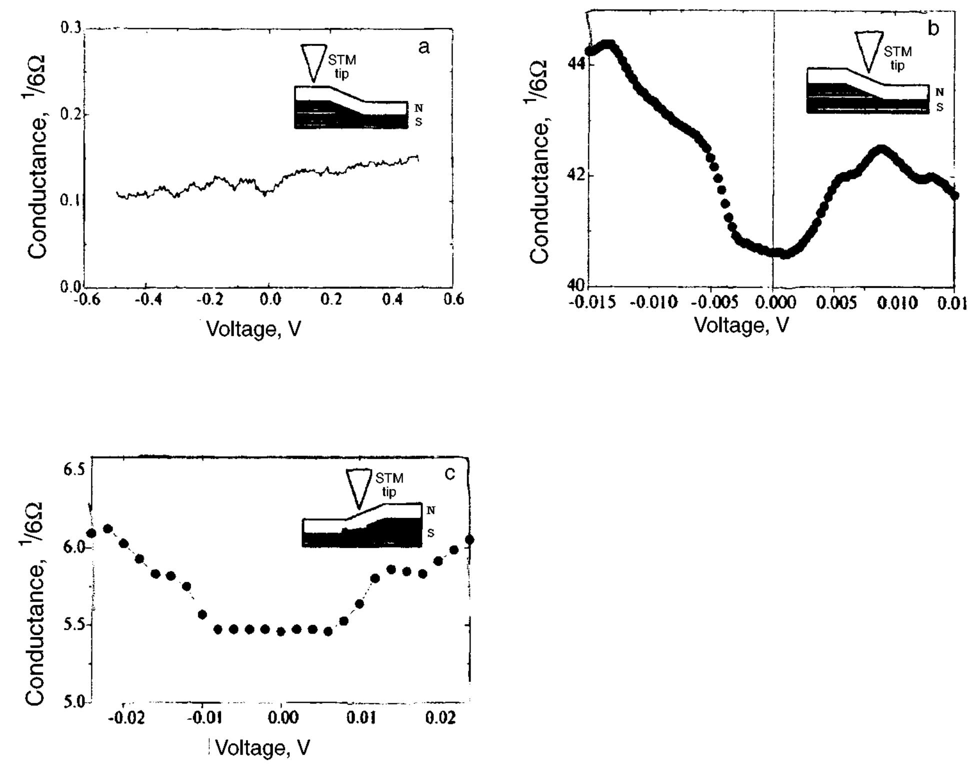

FIG. 2. Conductivity spectra obtained with a STM at different points of the surface of the structure with N-layer thicknesses of 20–30 nm. Insets: Position of the STM tip with respect to different sections of the SN boundary.

virtually identical to the IVCs obtained in samples with a thick gold film. Within the existing measurement accuracy, no features were recorded in the IVCs (Fig. 2a).

The typical form of the spectrum of the second type is shown in Fig. 2b. Features with a width from 2 to 7 mV (at half depth) were recorded near zero voltage. As a rule, such IVCs were observed on nonhorizontal sections of the surface.

Finally, the most infrequently recorded IVCs—the IVCs of the third type—contained features with a width of about 20 mV (see Fig. 2c).

DISCUSSION

The fact that stable images of the surface of the gold films were obtained indicates that the gold films were of good quality (no discontinuities) and that the electrical contact between the superconducting and gold film was good, i.e., there was no insulating layer between them over a quite large area.

In contrast to direct STM investigations of the surface of YBCO single crystals,[14,15] the explanation of the observed features in the IVCs cannot be attributed to one-electron effects or a Coulomb blockade of the resonance-tunneling channels.[16] For the Au granule sizes present ($\sim$40 nm), at temperatures close to 77 K the one-electron features should be completely smeared out.[17]

The existence of three types of IVCs are, we believe, different manifestations of the proximity effect in the YBCO/Au system (see insets in Figs. 2a and 2b).

In the first case (Fig. 2a), IVCs of N–C′–NS structures were observed in which the NS boundary was oriented perpendicular to the crystallographic c axis. In accordance with existing experimental data and theoretical estimates,[6,18,19] the transmittance of such a boundary is so low that the effective gap induced in the density of states in the N metal $\Omega \sim \Delta/\gamma_B \approx 20\ \mu$eV falls in a range of voltages outside the accuracy of the measurement system. In this situation, IVCs close to the N–C′–N type should be recorded.

Characteristics of the second type were observed on the sections of the sandwich where multiple emergence of CuO planes at the boundary was present with a high probability. In this geometry a suppression parameter $\gamma_B \approx 10$ and an effective gap $\Omega \approx \Delta/(1+\gamma_B) \approx 2$ meV in the density of states at the free gold boundary (N–C′–NS structure) are reliably recorded in the measurements. The experimental values of Ω fall in the range 2–4 meV, which gives for the suppression parameter $\gamma_B \approx 5-10$ close to the theoretical estimates.

Finally, in the third case we have a N–C′–N–C–S junction, formed by the STM tip and the gold film, in contact with a geometrically small section where the CuO planes emerge at the interface. When this section is traversed, a double ballistic contact is formed, making it possible to record features which are associated with both the superconducting gap[9,11] (i.e., lying in the voltage range 20–30 mV) and the effective gap induced in the N metal by the proximity effect.

The local spectroscopy data obtained for the YBCO/Au boundary indicate that as a result of its complicated morphology, the interface contains sections characterized by completely different transport properties. This feature explains not only the nonreproducibility of the parameters of the high-T_c superconductor in SNS Josephson junctions, but it also makes it possible to develop models which explain from a unified standpoint all the experimental data obtained in such structures.

We thank S. N. Polyakov for performing the x-ray diffraction measurements on the samples.

This work was supported by the subprogram ''Superconductance'' of the Russian GNTP ''Topical Problems in Condensed-Matter Physics,'' Grant No. 93018, as well as the International Science Foundation (Grants MNM000 and MNM300).

[1] M. S. Dilorio, S. Yoshizumi, K. Y. Yang *et al.*, Appl. Phys. Lett. **58**, 2552 (1991).
[2] M. S. Dilorio, S. Yoshizumi, K. Y. Yang *et al.*, in *Advances in Superconductance*, edited by Y. Bando and H. Yamoauchi, Springer, Tokyo, 1993, p. 1161.
[3] R. H. Ono, J. A. Beall, M. W. Cromer *et al.*, Appl. Phys. Lett. **59**, 1126 (1991); P. A. Rosenthal, E. N. Grossman, R. H. Ono, and L. R. Vale, Appl. Phys. Lett. **63**, 1984 (1993).
[4] N. Missert, T. E. Harvey, R. H. Ono, and C. D. Reintsema, Appl. Phys. Lett. **63**, 1190 (1993).
[5] R. H. Ono, L. R. Vale, K. R. Kimmenau *et al.*, IEEE Trans. Appl. Superconductivity **AS-3**, 2389 (1993).
[6] M. Yu. Kupriyanov and K. K. Likharev, Usp. Fiz. Nauk **160**, 49 (1990) [Sov. Phys. Usp. **33**, 340 (1990)].
[7] M. Yu. Kupriyanov and K. K. Likharev, IEEE Trans. Magn. **MAG-27**, 2460 (1991).

[8] A. V. Zaĭtsev, JETP Lett. **51**, 41 (1990).
[9] A. F. Volkov, A. V. Zaitsev, and T. M. Klapwijk, Physica C **210**, 21 (1993).
[10] A. A. Golubov and M. Yu. Kupriyanov, in *Extended Abstracts of International Conference on Superconductor Electronics*, Nagoya, Japan, 1995, p. 135.
[11] A. A. Golubov, and M. Yu. Kupriyanov, JETP Lett. **61**, 851 (1995).
[12] M. Koyanagi, S. Kashiwaya, H. Akoh *et al.*, Jpn. J. Appl. Phys. **31**, 3525 (1992).
[13] V. S. Édel'man, Prib. Tekh. Éksp., No. 5, 25 (1989).
[14] P. J. M. van Bentum, L. E. C. van de Leemput, T. M. Smokers, and H. van Kempen, J. Microsc. **152**, 11 (1988).
[15] P. J. M. van Bentum, L. E. C. van de Leemput, T. M. Smokers, and H. van Kempen, Phys. Scr. **25**, 122 (1989).
[16] I. A. Devyatov and M. Yu. Kupriyanov, Zh. Éksp. Teor. Fiz. **104**, 3897 (1993) [JETP **77**, 874 (1993)].
[17] D. V. Averin and K. K. Likharev, in *Mesoscopic Phenomena in Solids*, edited by B. L. Altshuler, P. A. Lee, and R. A. Webb, 1991, p. 173.
[18] A. A. Golubov and M. Yu. Kupriyanov, Zh. Éksp. Teor. Fiz. **96**, 1420 (1989) [Sov. Phys. JETP **69**, 805 (1989)].
[19] M. Yu. Kupriyanov, in *Advances in Superconductance*, edited by Y. Bando and H. Yamauchi, Springer, 1993, p. 1049.

Translated by M. E. Alferieff