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RESISTANCE ANOMALY NEAR SUPERCONDUCTING-NORMAL METAL INTERFACE*

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Resistance anomaly in high-temperature superconductors (HTS) $YBa_2Cu_3O_x$ (YBCO) and $Bi_2Sr_2CaCu_2O_y$ (BSCCO) thin film microstrips, covered by gold thin film, was observed. The resistance of the microstrip bilayer increases up to about 30% above the bilayer normal state resistance R_N at the beginning of the superconducting phase transition. Although in a number of recent publications, reporting an increase of the electrical resistance above the superconductor normal state resistance R_n, concerning of nonequilibrium quasiparticle and pair electrochemical potentials in mesoscopic systems, or as a result of structural nonhomogeneity of the samples, we argue that the resistance anomaly in our HTS/Au bilayers is associated with the proximity effect that accompanies superconducting-normal metal interface. The sharpness of resistance peak confirms a possibility to prepare HTS/Au interface with very high quality.

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1 Introduction

A number of recent papers [1-4] have reported on the occurrence of an anomalous and very sharp peak in the resistance versus temperature dependence at the onset of superconductor phase transition from the normal to superconducting state. Besides papers showing the extrinsic origin of such "resistance peak" induced by the detection of an external rf field in superconducting weak links [5], or by a strong nonhomogeneity of a film [6], there are many publications reporting on a systematic occurrence of such a resistance peak (RP) in mesoscopic superconducting structures (geometrical dimensions comparable to the coherence length $\xi(T)$ and the effective penetration depth $\lambda_{eff}(T)$) due to a long-range of phase-coherent effects at the superconductor-normal metal (SN) interface [7, 8]. Near the onset of the critical temperature T_{con}, at which the probability of Andreev reflexions at the SN interface is reduced, a nonequilibrium distribution of quasiparticles creates a charge imbalance, which gives rise to a difference in the chemical potentials of quasiparticles and Cooper pairs [1]. The charge imbalance length $\Lambda_Q = (D\,\tau_Q)^{1/2}$, where D is the diffusion coefficient and τ_Q the charge imbalance relaxation time, can be several microns long in superconductors with a large coherence length $\xi(T)$, such as aluminium, and it can induce a RP (up to several tens percents above a normal resistance R_n) near the SN interface or in a vicinity of the phase-slip centre (PSC) [9]. The resistance peak can be recorded if the distance between the voltage probe (on the superconducting side of the SN interface) and the SN interface is shorter than Λ_Q. Therefore this effect is at present practically impossible to observe in HTS because of the small coherence lengths. The amplitude of the RP strongly depends on applied current and magnetic field, and it is totally depressed by magnetic fields above 15 mT [4].

A close connection between a superconductor (S) and a normal metal (N) allows Cooper pairs to penetrate from S into the N, and on the contrary, electrons from N into the S. For isotropic superconducting thin films of thickness $d_S \gg \xi_0$, the critical temperature T_c at the SN interface is depressed by $\Delta T_c = -\gamma^2\pi^2\xi_0^2 T_c/4d_S^2 \approx 1.35 T_c(\xi_0/d_S)^2$, where ξ_0 is zero temperature coherence length of S and $\gamma \approx 0.74$ is a numerical factor. ΔT_c may be relatively large (several K) in the case of low temperature superconductors. On the other hand, the normal metal undergoes a transition into the S state due to the penetration of Cooper pairs in a thickness ξ_N. In the dirty limit (mean free path in N $l_N \ll \xi_N$) this thickness corresponds to the coherence length $\xi_N = (\hbar D/2\pi k_B T)^{1/2}$, where $\hbar$ is the Planck constant and k_B the Boltzmann constant. In the case of anisotropic (d-wave, s+d wave) high-T_c superconductors, the transmission coefficient of charge carriers strongly depends on the angle between the symmetry axis (a or b-axis) of the HTS and the normal to the SN interface. Transmission through the SN interface is the largest in the direction along which the order parameter $\Delta(T)$ is minimal. Therefore the morphology, roughness and anisotropy of the HTS thin film in close contact with the normal metal can strongly influence the properties of the SN interface [11].

SNS contacts, containing a double SN interface, are very frequently incorporated in various types of low-T_c and high-T_c superconducting circuits and devices based on Josephson tunneling effects (SQUIDs, analog and digital circuits, etc.). Therefore, the proximity effect has attracted considerable interest, both in theory [10, 11] and experiment [12]. Its presence in SNS junctions, especially in the case of superconductors with small coherence lengths (e.g. HTS), causes considerable problems in the preparation of SN interfaces of very high quality (sharpness). In this paper we present a study of electrical properties of $YBa_2Cu_3O_x$ (YBCO) and $Bi_2Sr_2CaCu_2O_y$ (BSCCO) superconducting thin film (thickness $d_S \approx 100$ nm) strips of submi-

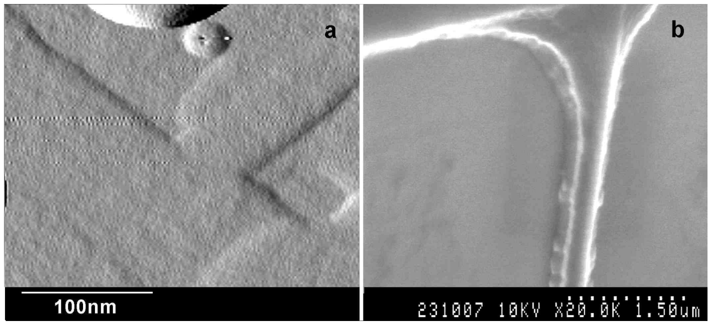

Fig. 1. STM micrograph of the surface of high-T_c superconductor thin film consisting from blocks (grains) connected by intergrain regions (a), and SEM micrograph of submicron width microstrip (b).

cron width $0.2 \leq w \leq 1.0$ μm, covered by a thin film of gold ($d_N \approx 100$ nm). A resistance peak in the $R(T)$ dependence was observed in our samples near the onset of the superconducting phase transition, which we interpret by the proximity effect at the SN interface of the structures studied. The sharpness of the resistance peak confirms negligible depression of interface critical temperature.

2 Sample preparation and measurements

Thin film bilayers of YBCO/Au were prepared by pulse laser deposition, and those of BSCCO/Au by dc magnetron sputtering on single crystal $SrTiO_3$ or $LaAlO_3$ substrates, respectively. An Au film was ex-situ deposited to a thickness of $d_N \approx 100$ nm (substrate at room temperature) immediately after the deposition of a HTS thin film. X-ray analyses confirm the single-phase epitaxial c-axis oriented growth of the HTS thin films. The films were patterned by ion beam etching through PMMA masks prepared by electron beam lithography. After the etching of the bilayers, a series of microstrips, with various width w ranging from 1.0 to 0.2 μm and length $L \approx 10w$, were measured in a temperature range 4-300 K and magnetic fields up to 30 mT. A series of individual microstrips in one row were connected with a 100 μm wide strips with the possibility to measure properties of these wide strips, as well. Resistance versus temperature $R(T)$ measurements were performed using a dc four-point method. The morphology of the film surface as well as the geometry of the microstrips are illustrated in Fig. 1. The STM image in Fig. 1a shows that the c-axis oriented HTS thin films were very smooth. They consisted of blocks (grains) with the size of several tens of nanometer (the surface of BSCCO is without Au) that were connected by an intergrain region. The microstrip geometry of YBCO or BSCCO films is shown in the SEM images of Fig. 1b.

3 Results and discussion

The critical temperature T_{con} (corresponding to the onset of HTS phase transition from N into S state) and the critical current density $j_c(T)$ of the as-deposited HTS films covered by Au were measured using a SQUID magnetometer [13] or using a magnetic susceptibility measurement technique. The measurement gave the values of $T_{con} = 89 - 91$ K, j_c(77 K) $\approx 5 \times 10^6$ A/cm^2 for the YBCO films and $T_{con} = 88 - 90$ K, j_c(77 K) $\approx 1 \times 10^6$ A/cm^2 for the BSCCO films,

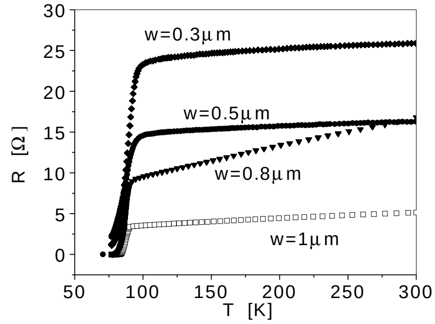

Fig. 2. Temperature dependence of YBCO/Au and BSCCO/Au thin film bilayer microstrip resistance. The resistance corresponds to microstrips 10 squares long ($L \approx 10w$). The superconducting phase transition width ΔT_c gradually increases for microstrips with smaller width w.

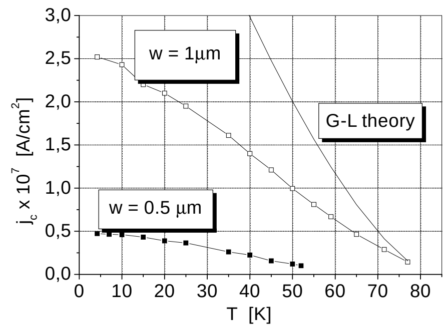

Fig. 3. The temperature dependence of critical current density for YBCO thin film microstrip of two different width w. Comparison with Ginzburg-Landau (GL) theory confirms some degradation effects on transport properties of microstrips.

with the width of the phase transition ΔT_c(bulk) in a range of 0.5-3 K. The values measured are typical volume ("bulk") properties of the films, and they do not characterise the SN interface. The temperature dependence of the microstrip (bilayer) resistance, without a resistance peak, is illustrated in Fig. 2 for microstrips of several different widths. The resistance of a high-T_c superconductor, at a temperature above T_{con}, is effectively shunted by a small resistance of Au. From the microstrip dimensions it can be determined that the resistivity ρ_n of Au is within the range 5 to 25 $\mu\Omega$cm at 300 K. This large resistivity of Au is probably affected by the morphology of HTS film and possibly by a chemical interaction of Au with the HTS, as well. The high value of ρ_n and a small R_{300}/R_{100} ratio for the Au film makes it reasonable to use the dirty limit for the calculation of the coherence length of Au $\xi_N \approx 8-10$ nm near 100 K ($D = v_F l_{el}/3 \approx 5 \times 10^{-3}$ m^2/s, where v_F is the Fermi velocity and l_{el} the electron mean free path). Fig. 2 shows that the width of the microstrip superconducting phase transition is much higher ($\Delta T_c(\text{strip}) \approx 10-20$ K) than that for the as-deposited (i.e. nonpatterned) bilayers. The reason lies in a partial oxygen loss during the ion beam etching (oxygen content was not optimize by annealing after patterning), as well as in the intergranular properties of the microstrips, because the percolation path of current is strongly directed by the narrow microstrip. The resistivity of the BSCCO/Au microstrips at $T > T_{con}$ is several times higher than that of the YBCO/Au microstrips, and it is evidently related to rougher BSCCO films prepared by dc magnetron sputtering as compared with the smoother

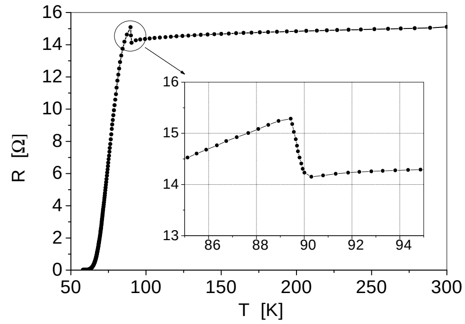

Fig. 4. Resistance anomaly (resistance peak) in the temperature dependence of resistance of YBCO/Au bilayer microstrip (width $w \approx 0.3$ μm). Inset shows the sharpness of the phase transition at the SN interface corresponding to phase transition of thin film grains.

YBCO films deposited by pulse laser ablation.

The temperature dependence of the critical current density $j_c(T)$ was estimated from the current-voltage characteristics of microstrip bilayers (placed in a magnetically shielded volume), and it was compared with the theoretical Ginzburg-Landau (GL) depairing critical current density $j_{cGL}(T)$ [14]. Fig. 3 illustrates the typical ability of submicron microstrips to transport high current densities in the superconducting state: j_c(4 K) $> 10^6$ A/cm^2 for $w \geq 0.5$ μm. The experimental values of $j_c(T)$ were several times smaller than the theoretical GL depairing critical current densities, which is probably caused by the granularity of the strips, and the effective width of the microstrips is probably shorter than the geometrical one due to a depression of superconductivity at the edges of the microstrip. (This will be discuss in more detail elsewhere.)

An unusual feature of the microstrips studied appeared as a pronounced resistance peak (RP) in $R(T)$ dependence near the onset critical temperature of the HTS/Au bilayer (Fig. 4). This RP was registered in about 25% of the samples measured. The RP amplitude did not depend on transport current (0.1 μA -1 mA) and magnetic field up to about 30 mT, in contrast to the effects observed in the mesoscopic structures of low temperature superconductors [3, 4, 7]. The increase of the RP in our samples was often very sharp (0.5-1 K, inset of Fig. 4), close to the ΔT_c(bulk), and the amplitude of the RP reached values up to 30% above the bilayer resistance R_N, depending on a local depression of superconductivity at the SN interface. The RP is not an intrinsic characteristic of the microstrips with the smallest width w, and it has been observed in 100 μm wide strips, as well. The resistivities of YBCO and BSCCO single layers are in normal state N 1-2 orders of magnitude higher than the resistivity of Au. Therefore, the HTS thin film is effectively shunted by Au unless the resistivity of HTS falls down in the region of the superconducting phase transition. The RP is sharp and easy to record if the depression of superconductivity at the SN interface is small. Simulations show that the amplitude of the RP quickly decreases in the region of a “bilayer phase transition” where, on the contrary, the resistance of Au is shunted by a lower resistance of the high-T_c superconductor (Fig. 4). If the microstrips were not covered by a normal metal, we never observed a RP both in YBCO and in more anisotropic BSCCO. Therefore, we can conclude that due to the proximity effect in an HTS/Au bilayer a small part of the Au thin film, with a thickness of approximately $\xi_N \approx 10$ nm (at 100 K), undergoes a transition into the superconducting state. In this case the resistance of the Au normal layer enhances proportionally to the thickness of the layer that becomes superconducting as the result of the proximity effect. The sharpness of the resistance increase depends on the width

ΔT_c of the HTS phase transition. Fig. 4 shows that the sharpness of the RP is close to that of the ΔT_c(bulk) of a non-patterned HTS/Au bilayer, and it is far away from a much wider microstrip phase transition ΔT_c(strip). This confirms that while the enhancement of the microstrip phase transition ΔT_c(strip) is given mainly by the properties (dispersion) of intergranular connections, the superconducting phase transition of the grains (superconducting blocks, Fig. 1a) ΔT_c(bulk) is not depressed and acts as the main factor in the proximity effect. Because the width of the RP was several Kelvin in some cases, we suppose that the roughness and crystallographic orientation of the HTS near the SN interface also play an important role in this effect.

4 Concluding remarks

In conclusion, we studied the properties of YBCO/Au and BSCCO/Au bilayer strips of sub-micron dimensions with the aim to determine the transport properties as well as their usefulness for SNS weak link devices. The microstrips are able to transport critical current densities above 10^6 A/cm^2 at temperature 4 K. This value can be enhanced by the optimization of the oxygen content through the annealing of the microstrips after the patterning of the structures. The resistance anomaly near the onset critical temperature was observed, which we ascribe to the proximity effect at the HTS/normal metal interface. The sharpness of the resistance anomaly reflects the role of bulk (grain) properties at the SN interface, i.e. the possibility for a minor degradation of interface, which give us hope for the realization of superconductor/normal metal/superconductor (SNS) sandwich junctions [16] with satisfactory properties for applications.

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