c-axis Tunneling in Nb/Au/YBaCuO Structures

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Abstract

We present the experimental results for Nb/Au/YBa$_2$Cu$_3$O$_x$ structures, in which the current flows along (001) direction of YBa$_2$Cu$_3$O$_x$ film. The theoretical evaluations show, that at the experimental values of the Au/YBa$_2$Cu$_3$O$_x$ interface transparency, determined from the interface resistance ($\bar{D} \sim 10^{-6}$), the critical current of the structure is of the fluctuation order of magnitude due to the sharp decrease of the amplitude potential of the superconducting carriers on this interface. Obtained I-V-curves could be interpreted in terms of contact between d-type pairing superconductor or gapless isotropic superconductor with normal metal. No critical current was observed for investigated structures with characteristic interface resistance $R_N S \sim 10^{-6} \Omega \cdot \text{cm}^2$, 2 orders of magnitude lower, than for known experimental data.

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1. Introduction

The properties of high-$T_c$ materials are discussed on the basis of the model of d-type symmetry of superconducting gap order parameter. This model explains, in particular, the dependence of the critical current from the magnetic field in bimetallic dc SQUIDs with junction YBa$_2$Cu$_3$O$_x$ (YBCO) and Pb [1] and the spontaneous excitation of the flux quantum in tricrystals [2]. But some experimental results are contradictory. On the one hand
there is no critical current in the junctions YBCO/s-superconductor along c-axis direction [3-5], which is in good agreement with the theory of tunneling between d-superconductors and s-superconductor; on the other hand, there are several experiments [6-8], where the evident critical current was obtained, which amplitude value changes from magnetic and microwave fields in accordance with the theory of s-superconductors. To explain the experiments [6-8] it was supposed [9], that there is a mixture of d and s-type superconducting carriers in high-T_c materials due to their orthorombic structure and the diffusive scattering near the interface or the twins in high-T_c films causes the increase of the contribution of s-superconductor [9,10]. Note, that the evaluation barrier transparencies (averaged over the quasiparticle momentum directions) for Pb/(Au, Ag)/YBCO presented in [6-8] gives $\bar{D} \sim 10^{-7} \div 10^{-9}$ with the junction areas $S = 0.1 \div 1mm^2$.

In this report we present the results of experimental investigations of current transport in the small areas junctions ($S = 8x8\mu m^2$) s-superconductor/normal metal/high temperature superconductor (Nb/Au/YBCO) with the averaged Au/YBCO c-axis interface transparency $\bar{D} \sim 10^{-6}$. The experimental results are analyzed from two points of view: classical BCS theory and modern theoretical investigations, where d-type symmetry of the order parameter in YBCO film is supposed.

2. Fabrication Procedure and Experimental Samples

The steps of the fabrication procedure are presented on the figure 1. YBCO thin films were made with two methods: the laser ablation technique and DC sputtering at high oxygen pressure. We used two kinds of substrates: (110) oriented NdGaO$_3$ or r-cut sapphire with CeO$_2$ buffer layer. So, we got c-axis oriented (001) epitaxial YBCO films with 100-150nm thickness. The following superconducting properties were obtained: the superconducting transition temperature $T_{cd}=84-88K$ and superconducting temperature width $\Delta T_{cd}=0.5-1K$; resistance ratio at 300K and 100K $R_{300K}/R_{100K} \approx 2.8$. The density of particles on the YBCO film surface was $\sim 10^6cm^{-2}$. The high quality of obtained YBCO films is confirmed by low
value of the width of X-ray (005) θ/2θ scan FWHM(005) ≈ 0.2° for 150nm thick YBCO film.

We used the following fabrication procedure of Nb/Au/YBCO junctions: a) Nb/Au/YBCO trilayer structure deposition; b) definition of the area of the junction with photolithography, ion and plasma chemical techniques; c) deposition of insulating CeO₂ layer to prevent the electrical contacts in a-b plane of YBCO; d) Contact pads deposition and structuring.

The thin layer of the normal metal (N-metal) (Au, Ag, Pt) 10-20nm thickness was deposited in-situ by RF sputtering after YBCO film deposition (fig.1a). The next step is the DC-magnetron deposition of Nb counter electrode 100-150nm thickness. The absence of chemical reaction between Au and Nb causes the using of Nb. Note, the possible chemical interaction between Au and Pb could be occurred in the experiments [4-7], where Pb is used.

On the next step the area of the junction was defined using the photolithography, ion and plasma-chemical etching (fig.1b). To prevent the electrical contact in a-b plane of YBCO film, the area of the junction with the central window 8x8μm² was insulated by CeO₂ layer using self-aligned technique (fig.1c). At the last step the contact pads from Au is formed(fig. 1d). We used the 2 points contact pads to the top (Nb) layer in order to realize 4 points measurement technique at the temperature below the T_c of YBCO film. The junctions were positioning on the parts of YBCO film surface, which had no particles. For measurement of and critical current density two orthogonal 4 μm width YBCO bridges were made on the same substrate. More than 30 samples Nb/N-metal/YBCO with Au, Ag and Pt as a N-metal were fabricated. Here we discuss the results of investigations of 9 samples Nb/Au/YBCO with the small tolerance of the normal resistance $R_N S$ (less than 4 times, see table 1) made with the same fabrication parameters.
3. Experimental results

The dependencies of the junction resistance from temperature $R(T)$ at bias current 1-5µA and I-V curves at temperature range 4.2-300K were measured. The fig.2 presents the $R(T)$ dependencies for one of the junctions and for YBCO bridge placed on the same substrate. The dependence $R(T)$ for one of the junction is in the good correspondence with one for YBCO microbridge, which is situated on the same substrate. At $T > T_{cd}$ $R(T)$ has a metallic dependence, i.e. the decrease of $R(T)$. This behavior is usual for a-b plane current flow, so YBCO film gives the main contribution to the resistance at $T > T_{cd}$. The inset to the fig.2 shows the $R(T)$ dependence of the junction at $T < T_{cd}$, the increase of the resistance with the decrease of temperature. The $R(T)$ value is dependent from the measurement current.

The dependencies of $R_d$ from the bias voltage are presented at fig.3 at different temperatures. The value of $R_d(V = 0)$ increase with the decrease of $T$, which is reflected on $R(T)$ dependence. The strong nonlinear behavior of I-V-curve at 72K<T<84K is due to a break down of superconductivity in YBCO film by transport current. Note, that there is a difference between the $R_N = R_d(0)$ of the junction near $T_{cd}$ and the asymptotic $R_N = R_d(V), V > 20mV$ at $T << T_{cd}$.

Parameters of the investigated junctions, fabricated at equal conditions, are presented in table 1. The interface resistance $R_NS$ allows to evaluate the averaged interface transparency, which will be used in future [11]:

$$ \tilde{D} = \frac{2\pi^2\hbar^3}{e^2p_F^2} \frac{1}{R_NS} = \frac{2\rho^{YBCO}\rho^{YBCO}}{3R_NS}, $$

where $p_F$ - the minimum value of Fermi-momentum from YBCO and Au. The values of transparency for the interface Au/YBCO are presented in the table 1 for fabricated samples.

We use the values $\rho^{YBCO}\rho^{YBCO} = 3.2 \cdot 10^{-11}\Omega \cdot cm^2$, $R_N = R_d(V)$ at $V = 20mV$.

We also investigated the bilayer structures Au/YBCO, Nb/YBCO and Au/Nb, prepared with the same technology as trilayer ones. The resistance of these interfaces are as follows: $R_NS(Au/YBCO) \approx 10^{-8}\Omega \cdot cm^2$, $R_NS(Nb/Au) \approx 10^{-12}\Omega \cdot cm^2$ and $R_NS(Nb/YBCO) \approx$
$10^{-4} \Omega \cdot cm^2$. From the comparison with the results presented in the table 1 for the junction Nb/Au/YBCO, we can neglect the Nb/Au interface resistance, and take into account only Au/YBCO interface resistance. $R_d(V)$ for Au/YBCO junctions show the similar behavior as $R_d(V)$ for Nb/Au/YBCO.

Figure 4 presents the surface of bilayer structure Au/YBCO, measured with the Atomic Force Microscope (AFM). One can see the strongly nonuniform surface, which consists of Au granules with about 1µm distance between its. So, there is a good electrical contact in the parts of the film, where Nb film covers Au granules on YBCO. But between the Au granules, where Nb film has direct contact with the surface of YBCO, the oxygen depletion on the surface of the structure causes the increase of the resistance. Direct electrical contact Nb/YBCO has the specific resistance 3-4 orders of magnitude higher than the Au/YBCO contact.

4. Discussion

We can consider the investigated structure as a parallel connection of grains Nb/Au/YBCO and the parts of the structure with direct contact Nb/YBCO. We suppose, that the current flows through Au/YBCO interface, because of the big resistance Nb/YBCO interface and we can use the schematic model, presented on the fig.5.: the superconducting electrode YBCO ($S_d$) with the critical temperature of the superconducting transition $T_{cd} = 87K$ and thickness 100-150nm; the damaged layer of YBCO ($S_d'$) 1-3nm thickness with suppressed superconducting order parameter; normal metal layer 10-20nm thickness; the superconducting Nb counter electrode ($S'$) with $T_{c0} = 9.2K$. The analogous model was suggested in [4] for the evaluation of the electrophysical parameters in the system Pb/Au/YBCO.

Let’s evaluate the behavior of the superconducting order parameter in such Nb/Au/YBCO structure. First, consider the Nb/Au interface. It’s measured resistance is low enough, so we can conclude, that superconducting Green function (which is the characteristic of the amplitude of the interaction potential of the superconducting carriers
Φ) and it’s derivative are continuous in the interface. Using calculations [12,13] we obtained the value of the superconducting order parameter at the interface $\Delta_1/e \approx 560 \mu V$, which is a bit smaller than in the bulk Nb. For our evaluations we used the following values of electrophysical parameters Nb and Au at $T = 4.2K$: $\rho^{Nb} = 4 \cdot 10^{-12} \Omega \cdot cm^2$, $\xi^{Nb} = 7.3 \cdot 10^{-7} cm$, $V_F^{Nb} = 3 \cdot 10^7 cm/s$, $T_{d_0}^{Nb} = 9.2K$ and $\rho^{Au} = 8 \cdot 10^{-12} \Omega \cdot cm^2$, $\xi^{Au} = 1 \cdot 10^{-6} cm$, $V_F^{Au} = 1.4 \cdot 10^8 cm/s$, where $V_F^{Nb,Au}$ - Fermi velocities and $l^{Nb,Au}$ - mean free paths of Nb and Au correspondingly.

For the YBCO/Au interface we suppose, that it could be the 3nm thickness damaged layer of YBCO $S'_d$ with the reduced critical temperature (may be nonsuperconductive). Let’s assume the small difference in the coherence length $\xi_{c-YBCO} = \xi_{S'_d} = 5 \cdot 10^{-8} cm$ and that the specific resistance increases for the order of magnitude [4] from $\rho_{c-YBCO} = 1 \cdot 10^{-4} \Omega \cdot cm$ to $\rho_{S'_d} = 1 \cdot 10^{-3} \Omega \cdot cm$. We have the value of the order parameter in YBCO near the Au/YBCO interface $\Delta'_2/e \approx 140 \mu V$ qualitatively. There is a potential barrier with the low transparency $\bar{D} \sim 10^{-6}$ direct on the Au/YBCO interface, which leads to the step of the order reduction in $\bar{D}$ times: $\Delta_2 = \Delta'_2 \bar{D}$ [13]. We used the theoretical evaluations for s-type pairing superconductors. But one can conclude from the evaluations [10,14], that the behavior of the order parameter in d-superconductor are qualitatively the same as for s-superconductor if one of the main crystallographic directions of d-superconductor is normal to the interface.

So, we can evaluate the amplitude value of the supercurrent through the whole structure as in the junction superconductor-normal metal-superconductor ($S'_dNS$), where values of the order parameter on the interfaces are $\Delta_2/e \approx 0.14nV$ and $\Delta_1/e \approx 560 \mu V$. Than we use the theory developed for SNS-junctions. The thickness of the N-layer is of the same order of magnitude, that it’s coherence length, so we can neglect the decrease of the order parameter in the N-layer and result $I_cR_N \approx \frac{\Delta_1\Delta_2}{e} \approx 0.09 \mu V$. Taking into account the value of the normal resistance of the junction $R_N = 10\Omega$, we get the value of $I_c \approx 0.009 \mu A$, which is less than the fluctuation one for the measurement system $I_f = 1 \mu A$ and could not be observed even in the case of the dominant s-type component. If we have the pure
$d_{x^2-y^2}$-superconductor, the critical current is equal to zero from the symmetry of the gap. The observed in [6-8] critical current in Pb/(Au,Ag)/YBCO structures with higher values of $R_N S$ and junction areas, possibly, caused by a soft etching in the Br-ethanol solution, which allows the current flow through the contacts to a-b planes of YBCO. The transparencies of the interfaces with normal metals in a-b planes of YBCO are 3 orders of magnitude higher, than along c-axis ($R_{ab} S_{ab} \ll R_c S_c$), but $S_{ab} \ll S_c$. So, the normal resistance resulted from the parallel connection of the interfaces along c-axis and a-b planes of YBCO is equal to $R_N S = R_c S$ if $S_{ab}/S_c \approx R_{ab} S_{ab}/(R_c S_c), S = S_{ab} + S_c$. In the case of Nb, the oxygen depletion in a-b planes is stronger than along c-axis, so the influence of a-b plane tunneling is significantly reduced.

The important fact is the possible interaction both with YBCO and Au with the formation of the superconducting alloy. In this case we have a superconductor with the low enough critical temperature instead of the normal metal, which could have a gap feature at low temperatures [6-8].

Let’s discuss the figure3 - the $R_d(V)$ dependencies for the junctions at 4.2-100K temperature range. At $T \ll T_{cd}$ the I-V curves correspond to the SIN junction: the increase of $R_d$ below the gap value. But there are no gap features of YBCO. These two facts correspond to a gapless s-superconductor or d-superconductor with the nodes [14,16]. Calculations [14] give the dependencies $R_d \sim \ln(T), \ln(|| eV | -\Delta |)$. Note, that for s-superconductor with gap we have $T^{-1/2}, ((eV)^2 - \Delta^2)^{-1/2}$.

For s-superconductors at $kT \ll \Delta$, the number of excited quasiparticles increases exponentially with the temperature, so $R_d(0) \sim \exp(-\Delta/kT)$. It could be a great number of excited quasiparticles even at very low temperatures $kT \ll \Delta$ in d-superconductors due to the existence of nodes with zero value of the order parameter. So, $R_d(0)$ must increase slower with the decrease of temperature [14]. In our experiment we have the linear $R(T)$ dependence with decrease of T (insert to a fig.2). The dependence $R_d(V)$ corresponds qualitatively to the theoretical calculations for d-superconductor [14].

One of the most interesting effects for d-superconductors is the existence of two types of
the bound states. The surface states at low energies caused by a sign change of the order
parameter for the reflected quasiparticles in the a-b plane of d- superconductor [14-16]. It
leads to a minimum value on $R_d(V)$ dependence at low $V$ I SIN junction, which was observed
for a-b plane current transport [6-8]. In our experiment we have no such effect due to the
quasiparticle momentum along c-axis of YBCO.

Another additional states could be present due to the suppression of the order param-
eter of d-type superconductor at the interface for the directions different from the main
crystallographic ones or in the case of the diffusive scattering [16]. These states are ob-
served at nonzero energies and weakly dependent from the temperature and the interface
quality. One could found these states as decrease of $R_d$ at the values of $V_d$ near the gap
of d-superconductor. The condition of the suppression of the order parameter is realized
in our experiment due to the degradation of YBCO surface. Really, we found the weak
minimum at $V \approx 15mV$ for all measured samples, which didn’t change it’s position from
the temperature.

5. Conclusion

Here we present the results of fabrication and experimental investigation of the electron
transport in Nb/Au/YBCO junctions along c-axis of YBCO. The transparencies of the bar-
riers are one order of magnitude higher the ones from [6-8]. The evaluations on the basis of
the proximity effect showed the absence the critical current cased by the Au/YBCO inter-
face potential barrier. The $R_d(V)$dependencies are analogous to the case of SIN junctions
with gapless superconductor, in particular, the absence of the gap feature for YBCO could
correspond to d-superconductivity, due to the existence of the nodes in the order parame-
ter. $R(T)$ dependencies are also in good agreement with the theory of d-superconductor.
At $V \approx 15mV$ one could see the sharp decrease of the $R_d$, which could be caused by the
additional states at the interface of the d-type superconductor with the normal metal.

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6. References

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7. Figure Captions

Fig.1. The fabrication procedure of YBCO/Au/Nb junctions: a) Nb/Au/YBCO trilayer structure deposition; b) definition of the area of the junction with photolithography, ion and plasma chemical techniques; c) deposition of insulating CeO$_2$ layer to prevent the electrical contacts in a-b plane of YBCO; d) contact pads deposition; e) top view of the junction.

Fig.2. The temperature dependence of the structure and of the 4$\mu$m width microbridge on the same substrate. The measurement current is 5$\mu$A. The insert presents the $R(T)$ dependence on a larger scale at $T < T_{cd}$. The resistance of microbridge is equal to zero at this temperature range.

Fig.3. Dependencies of the differential resistance of the structure at different temperatures. Right axis shows the scale for T=91K.

Fig.4. Surface of the structure Au/YBCO, obtained by AFM.

Fig.5. Schematic dependence of the order parameter and amplitude of the pair potential values in direction perpendicular to the junction plane.

8. Table 1

Parameters of fabricated junctions, measured at T=4.2K.
Sample $R_d(0), \Omega R_N(V), \Omega R_N S, 10^{-6}, \Omega \cdot cm^2 R_d(0)/R_d(V) \bar{D}, 10^{-6}$

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| P9J2 | 12.2 | 7.0 | 4.5 | 1.7 | 4.8 |
| P9J3 | 9.8 | 6.0 | 3.8 | 1.6 | 5.6 |
| P10J2 | 10.5 | 5.9 | 3.8 | 1.8 | 5.6 |
| P10J3 | 10.6 | 5.9 | 3.8 | 1.8 | 5.6 |
| P11J2 | 4.9 | 4.2 | 2.7 | 1.2 | 7.9 |
| P11J3 | 5.2 | 3.6 | 2.3 | 1.4 | 9.3 |
| P12J2 | 2.4 | 2.0 | 1.3 | 1.2 | 16.7 |
| P13J2 | 7.2 | 3.5 | 2.2 | 2.1 | 9.5 |
| P13J3 | 7.5 | 6.6 | 4.2 | 1.1 | 5.1 |
