TRANSPORT PROCESSES AND REDUCTION OF $I_c R_n$ PRODUCT IN $YBa_2Cu_3O_x/PrBa_2Cu_3O_x/YBa_2Cu_3O_x$ RAMP-TYPE JOSEPHSON JUNCTIONS

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Abstract--The mechanisms of the current passage and the reasons of $I_c R_n$ product reduction of the YBCO/PBCO/YBCO ramp-type junctions are analyzed. At PBCO barrier thicknesses $L=8-20$ nm the junction characteristics are determined by the thickness of the PBCO barrier and its nature. The boundary resistance and depression of the YBCO superconducting parameters near the interface do not strongly affect the junction parameters. The behavior of the YBCO/PBCO/YBCO junctions can not be described by simple SNS weak-link or SIS tunnel models. A strong pair-breaking effect and an one-center inelastic tunneling process are taken into account to explain the Josephson and normal state characteristics of these junctions.

I. INTRODUCTION

Important questions for the basic study of the Josephson and normal-state characteristics of the high- T_c (HTS) Josephson junctions are: 1) the type of the structure (SNS weak-link or SIS tunnel junction); 2) the reasons of $I_c R_n$ product reduction; 3) the influence of the barrier nature and interface quality on the junction behavior; 4) the mechanisms of the supercurrent and quasiparticle-current passage. These questions often remain unclear for many of the proposed HTS junctions, despite their good Josephson behavior.

A similar crystal structure of HTS $YBa_2Cu_3O_x$ (YBCO) and its nonsuperconducting isomorph $PrBa_2Cu_3O_x$ (PBCO) gives the opportunity to produce high-quality heteroepitaxial YBCO/PBCO/YBCO multilayers and Josephson structures. The fabrication process and characterization of the YBCO/PBCO/YBCO ramp-type junctions with PBCO barrier thickness $L=8-20$ nm have been reported previously [1,2]. Our study shows a high quality of the crystal structure of the layers and reproducible electrical characteristics. The junctions show clear Josephson behavior as well as scaling of the junction parameters with cross-section area A .

In the present work we analyze the above mentioned four questions for the YBCO/PBCO/YBCO ramp-type junctions with a thick PBCO barrier, $L=8-20$ nm. To estimate the effect of the interlayer boundary resistance we discuss also the behavior of the YBCO/YBCO junctions without PBCO barrier.

II. EXPERIMENTAL RESULTS AND DISCUSSION

A. YBCO/YBCO ramp-type junctions.

A similar crystal structure of YBCO and PBCO layers and the implemented epitaxial growth can provide low carrier scattering at the interfaces between the layers of the junction. However, the parameters of the YBCO base electrode near the interface can be depressed due to Ar ion etching of the edge surface of the YBCO base electrode. To estimate the influence of the ex-situ fabrication process, we studied the properties of YBCO/YBCO ramp-type junctions without PBCO barrier layer. These junctions have been prepared under similar process conditions, including ion beam etching and edge-surface cleaning processes. The absolute values of the critical current density $J_c(T)$ of YBCO/YBCO junctions is several orders of magnitude higher, than that of the YBCO/PBCO/YBCO junctions with a thickness of PBCO barrier $L=6-8$ nm. The upper limit of the interface resistance R_B for YBCO/YBCO junctions is estimated to be $R_B \leq 3 \cdot 10^{-9} \Omega \cdot \text{cm}^2$. These results can be used for the analysis of the YBCO/PBCO interface quality. Due to a similar crystal structure, the interface resistance between the YBCO and PBCO layers is suggested to be in the same range of values. The values of $R_B \leq 3 \cdot 10^{-9} \Omega \cdot \text{cm}^2$ are negligible in comparison with typical values of R_n of the YBCO/PBCO/YBCO junctions with a PBCO barrier thickness $L=8-20$ nm, where $R_n \sim 10^{-7}-10^{-5} \Omega \cdot \text{cm}^2$.

B. YBCO/PBCO/YBCO ramp-type junctions.

To clarify the role of the PBCO barrier layer on the strength of the Josephson coupling, a comparison of the dependence of the critical current density J_c on the specific junction resistance $R_n A$ in different types of HTS junctions is shown in Fig. 1. Different types of junctions give similar J_c values (similar strength of the Josephson coupling) at different $R_n A$ values. At $J_c \sim 10^2-10^4$ A/cm², the $R_n A$ values are $\leq 10^{-8} \Omega \cdot \text{cm}^2$ for low-ohmic weak-link structures, $\sim 10^{-8}-10^{-7} \Omega \cdot \text{cm}^2$ for grain-boundary junctions (GBJ) and $10^{-7}-10^{-5} \Omega \cdot \text{cm}^2$ for YBCO/PBCO/YBCO ramp-type junctions (see Fig. 1). Thus, in YBCO/PBCO/YBCO junctions the superconducting banks are coupled through the barrier with the highest resistivity in comparison with the other HTS Josephson junctions.

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Fig.1. Critical current density as a function of the specific junction resistance $R_n A$ of the different junctions: YBCO/PBCO/YBCO junctions (marked by triangle, curve A); GBJ on SrTiO_3 bicrystals (from ref. [3], marked by cross, curve B); GBJ on MgO crystal (ref. [4], marked by diamond, curve C) and YBCO/N-YBCO/YBCO junctions (from ref. [5], marked by square).

The effective coherence length of the PBCO barrier layer was estimated as $\xi_n \sim 5-8$ nm from the thickness dependence of the critical current density $J_c(L)$ [2]. Thus, at barrier thicknesses $L > \xi_n$ the YBCO/PBCO/YBCO junctions can be treated as junctions with a thick barrier. However, the temperature dependence of the junction resistance R_n is not typical for a SNS structure with a thick ($L > \xi_n$) barrier. For SNS structures with $L > \xi_n$ and $L \gg l$ (l is the mean free path of the carriers), R_n is the sum of the N-layer resistance R_p and the boundary resistances R_B :

$$R_n \sim R_p + R_{B1} + R_{B2} \quad (1)$$

As we discussed earlier, the boundary resistance R_B is negligible for these structures compared to the absolute values of R_n . Thus, for large thicknesses of the barrier, $L > \xi_n$, R_n must reflect the semiconductor-like temperature dependence $R(T)$ for PBCO bulk material. Meanwhile the junction resistance R_n varies insignificantly at low temperatures and thicknesses of the barrier $L \sim 8-20$ nm, as we discussed in detail in [6].

A temperature-independent behavior of the junction resistance is more typical for tunnel type junctions and can not be described by an SNS model. In the YBCO/PBCO/YBCO junctions the Josephson coupling is established through a high-resistive barrier layer. With respect to these characteristics and high values of specific resistance $R_n A$, the junctions are better described by a SNINS tunneling model. Nevertheless, the RSJ-like current-voltage characteristics and the excess current at barrier thicknesses $L = 6-20$ nm resembles the features of weak-link structures, as we discussed in [2]. Therefore the YBCO/PBCO/YBCO junctions can hardly be described by simple SNS weak-link or SIS tunnel models.

C. Inelastic tunneling via localized states.

The mentioned discrepancy between the description of the junction characteristics can be overcome if an inelastic tunnel processes through the barrier is taken into account. The presence of the defects or the impurity states in the tunnel barrier can facilitate the current passage between the electrodes. Depending on the thickness and the nature of the barrier, the concentration and the location of the impurities in the barrier, different mechanisms of the resonant or inelastic tunneling can be realized, as was discussed earlier in [6]. The nonsuperconducting current can be carried via localized states by inelastic tunneling. Such a mechanism changes the normal state resistance of the junction and can be the reason of the RSJ-like current-voltage characteristics at the voltages V lower than the width B of the impurity conductive band, $|V| \leq B$. The width of the conductive band B :

$$B = n_L a_0^3 (E_c - E_F) \exp[-1/n_L a_0] \quad (2)$$

depends on the density n_L and Bohr radius a_0 of the localized states, the height and the thickness of the barrier [7]. The conductivity of the junction due to inelastic tunneling depends on the number of the impurities in the channel [8]. The temperature- and voltage-independent channels are direct tunneling and one-impurity inelastic tunneling. These mechanisms are dominant at low temperatures or at low density of the localized states. Thus, the current passage via inelastic scattering at one effective localized center seems to be the reason for both the SNS-like shape of the current-voltage characteristics and the temperature-independent normal state junction resistance at PBCO barrier thicknesses $L \sim 8-20$ nm.

Inelastic tunneling via localized states facilitates the passage of the nonsuperconducting current through the barrier, but can not explain the fast decrease of the $I_c R_n$ product with barrier thickness and dependence of $I_c R_n$ products on temperature.

D. Proximity and strong pair-breaking effects in YBCO/PBCO/YBCO junctions.

For HTS-based SNS structures with Ag or Au as a N-layer the depression of the superconducting order parameter near the interface and in the barrier can be described well by proximity effect models [9, 10]. However, for the YBCO/PBCO/YBCO structures the proximity effect is quite different, than that for SNS structures with low-ohmic N-layer [6]. Using the experimental data $\rho_n = R_n A / L \sim 0.3-3 \Omega \cdot \text{cm}$, $\xi_n = 6 \cdot 10^{-7} \text{ cm}$ and $R_B < 10^{-8} \Omega \cdot \text{cm}^2$ we find the values of the proximity-effect parameters for YBCO/PBCO/YBCO structures

$$\gamma = \rho_s \xi_s / \rho_n \xi_n \sim 10^{-4} \quad \gamma_B = R_B / \rho_n \xi_n \sim 10^{-1} \quad (3)$$

Here ρ is the normal state resistance and ξ is the coherence length, the indices s and n refer to the YBCO and PBCO layers, respectively. Small values of the proximity effect parameters reflect: 1) a small

Thus, the resistance of the junction is determined by the channel with the lowest resistance. At small thickness of the barrier and at low temperatures the junction resistance can be determined by an one-center inelastic tunnel channel which is temperature-

Fig.4. Temperature dependences of the resistance of the inelastic-tunneling channels with N localized centers for a small thickness of PBCO barrier. The values of resistance are in relative units.

independent, as shown in Fig. 4 for $T \leq 80$ K. At higher temperatures or at a thicker barrier the resistance of the one-impurity channel can be relatively higher than that of the two-impurity channel, and the junction will have a temperature-dependent resistance. In the case of the multitude of the localized centers in the channels with the lowest resistance, the total junction resistance gradually transforms in a variable-range hopping dependence in a wide temperature range (Mott law) [9]:

$$R(T) = R_0 \exp \left([T_0/T]^{1/4} \right) \quad (4)$$

Experimental measurements shows variable-range hopping transport for bulk PBCO samples [13] and semiconducting-like dependence of the YBCO/PBCO/YBCO junction resistance at barrier thicknesses $L \sim 100$ nm [13].

The value of the pair-breaking parameter $\tau_s^* \sim 1/\pi T_c$ is also in qualitative agreement with the estimate of the spin-flip scattering time for PBCO. In the $Y_{1-y}Pr_yBa_2Cu_3O_x$ compound T_c decreases gradually with increase of the Pr content down to $T_c=0$ at $y \sim 0.55$. According to the Abrikosov-Gor'kov theory for the depression of T_c by spin-flip impurities [14], vanishing of T_c to zero corresponds to a spin-flip scattering time $\tau_s^* \sim 3.56/\pi T_c$. Doubling the Pr content ($y \sim 1$) approximately decrease the scattering time τ_s^* by the factor of two. Thus, the value of $\tau_s^* \sim 1/\pi T_c$, used in the description of $I_c R_n(T)$ and $I_c R_n(L)$ dependences, is in reasonable agreement with the estimate of τ_s^* for PBCO. However, for a further analysis and a quantitative description of the junction behavior more information about the effect of Pr on the behavior of PBCO is needed.

III. SUMMARY

The characteristics of the YBCO/PBCO/YBCO structures are determined by the thickness of the PBCO barrier and its nature. The junction characteristics can not be described completely by simple SNS weak-link or SIS tunnel models. The proposed explanation of the junction behavior by taking into account a strong pair-breaking effect in the barrier and one-impurity inelastic tunneling agrees qualitatively with hopping conductivity and destruction of the superconductivity by strong pair-breaking effect in bulk PBCO.

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Fig.2. Dependence of the $I_c R_n$ products on the barrier thickness. Experimental data are marked by square and fitted by the solid curve. Calculated $I_c R_n(L)$ dependencies: SNINS structure with $\gamma_b \ll 1$ and ξ_n : 8 nm (curve 1) and 5 nm (curve 2); SNINS structure with $\gamma_b \ll 1$, $\tau^* = 1/\pi T_c$ and ξ_n : 7 nm (curve 3) and 5 nm (curve 4).

depression of the superconducting order parameter of the YBCO layer due to the contact with high-ohmic PBCO barrier layer and 2) a low boundary resistance R_b in comparison with the resistance of PBCO barrier layer.

Proximity effect models can not explain the thickness and temperature dependence of the $I_c R_n$ product. Fig. 2 shows the dependence of the $I_c R_n$ products on the PBCO barrier thickness. The experimental data are given by the squares and the solid line. Curves 1) and 2) are theoretical $I_c R_n$ dependencies of the proximity-effect model [10] for $\gamma_b \ll 1$ and different values of ξ_n : 8 nm (curve 1) and 5 nm (curve 2).

Fig.3. Temperature dependencies of the $I_c R_n$ products of the junctions with PBCO barrier thicknesses: a) 20 nm 2) 8 nm. Experimental data are fitted by the solid lines. Curves 1-3 are calculated dependencies for: 1) SNS structure with $L/\xi_n = 2$ and large γ_b value; 2) SNINS structure with $L/\xi_n = 2$ and $\gamma_b \ll 1$; 3) SNINS structure with $L/\xi_n = 1.5$, $\gamma_b \ll 1$ and pair breaking parameter $\tau^* = 1/\pi T_c$.

Better fitting is possible only at lower values of $\xi_n \leq 1-2$ nm, which is inconsistent with the $J_c(L)$ dependence for barrier thicknesses $L \geq 10$ nm.

Two typical dependences of the $I_c R_n$ products on temperature are shown in Fig. 3 as curves a) and b) (solid lines). For curve a) we try to find the theoretical $I_c R_n(T)$ dependence by using the proximity-effect models [9, 11]. Using $I_c R_n(T)$ dependences from Ref. [10] for SNS structures for $L/\xi_n = 2$ and large values of γ_b we obtain curve 1 (dotted line). A large value of γ_b is needed to fit the $I_c R_n$ value at $T = 4$ K. The discrepancy with the experimental data (curve a) is large at all temperatures. Using the $I_c R_n(T)$ dependence of SNINS structures for $L/\xi_n = 2$ and small values of γ_b (dash-dotted line), the discrepancy is reduced especially at low temperatures but the agreement is still not satisfactory. The calculated $I_c R_n(T)$ dependencies for SNS or SNINS structures with a lowered $I_c R_n$ product due to the proximity effect have a shape, which is different from the experimental ones.

A sufficiently good description of the $I_c R_n(T)$ dependence and the values of the $I_c R_n$ product at different barrier thicknesses is obtained by taking into account the carrier scattering at localized pair-breaking centers in the barrier. We found good agreement with the experimental data using a model for SNINS structures with strong pair-breaking in the barrier [11]. The calculated $I_c R_n(T)$ dependence for SNINS structures with $L/\xi_n = 1.5$, $\gamma_b \ll 1$ and a temperature independent pair-breaking parameter $\tau^* = 1/\pi T_c$ is shown in Fig. 3 as curve 3 (dashed line). In addition, the calculated $I_c R_n(L)$ dependence for $\xi_n = 7$ nm, $\gamma_b \ll 1$ and $\tau^* = 1/\pi T_c$ (Fig. 2, curve 3) fits the experimental data better than proximity-effect models. Thus, the pair breaking mechanism gives a strong temperature independent suppression of the $I_c R_n$ products which may explain our experimental data of $I_c R_n(T)$ and $I_c R_n(L)$.

E. Comparison with behavior of bulk PBCO.

The proposed explanation of the YBCO/PBCO/YBCO junction behavior agrees with the experimental data for bulk PBCO. First, we can show qualitatively a gradual transformation of the temperature-independent junction resistance R_n into the variable-range hopping transport for bulk PBCO upon increase of the barrier thickness.

The conductivity of the inelastic tunneling depends strongly on the total number and density of localized centers in the channel and hopping strength of these centers [9]. Fig. 5 shows the temperature dependences of the resistivity of the channels with N hopping centers. The calculations have been made according to the Glasman-Matveev model [8] for $N = 1-4$, properly chosen small thickness of the barrier, $L \sim a_0$, and the small density of the localized states. In the junction all the channels are connected in parallel.