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Excess Conductivity of $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-x}$ Single Crystals

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In this work we investigate the conductivity in the basis plane of $YBa_2Cu_3O_{7-x}$ and $Y_{1-z}Pr_zBa_2Cu_3O_{7-x}$ single crystals with a system of one-direction twin boundaries. The Pr dopants behave as efficient scattering centers of normal and fluctuating carriers. For this a slight doping with praseodymium (till $z \approx 0.05$) results in a significant narrowing of the temperature interval in which the pseudo-gap regime is realized in the *ab*-plane of YBaCuO single crystals.

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1. Introduction

$RBa_2Cu_3O_7$ (R = Y and lanthanides) compounds are of technological importance as high-temperature superconductors because of their high critical temperature (T_c) of about 90 K. In $YBa_2Cu_3O_{7-x}$ (YBCO) the partial substitution of Y with Pr results in the suppression of superconductivity (in distinction to the Y substitution with other rare-earth elements), and allows one to keep practically unchanged the lattice parameters and the oxygen stoichiometry [1–3]. Pr substitution is important for the understanding of the nature of high temperature superconducting compounds (HTSC) and for the interval in which the pseudo-gap (PG) regime is realized [3].

The investigation of the presence or absence of superconductive properties in compounds of identical crystal structure and the understanding of the conditions under which the phenomenon is not present can be important. This is highlighted by the amount of experimental work aiming at explaining the "praseodymium anomaly" [2]. The transport properties of HTSC are dependent on the type and concentration of defects and the oxygen stoichiometry [1–3].

It is worth noting that until today the experimental data concerning the Pr dopants influence on the transport properties of YBCO compounds remains considerably contradictory. This is because a large amount of experimental work was carried out on ceramics, films and textured samples with different methodologies. The studies that were carried out on single crystals (for example see [3]) were on samples with Pr concentrations exceeding 15%.

The aim of this work is to study the effect of slight Pr doping (up to 5%), in different conductivity regimes in the YBCO single crystals with high T_c having unidirectional twin boundary (TB) system.

2. Experimental techniques

The growth and oxygen saturating regimes and the resistivity measurement methods are described in detail in previous studies [4, 5]. To obtain samples with an optimal oxygen content ($\delta < 0.1$), crystals were simultaneously annealed together in an oxygen flow at a temperature of 400°C for five days [4]. The transport current vector, $\boldsymbol{I}$, was parallel to the twin planes (Fig. 1). The temperature dependences of the electric resistivity in the ab-plane, $\rho_{ab}(T)$, for the YBCO (K1) and $Y_{1-z}Pr_zBa_2Cu_3O_{7-x}$ (K2) crystals is shown in curves 1 and 2 of Fig. 1, respectively.

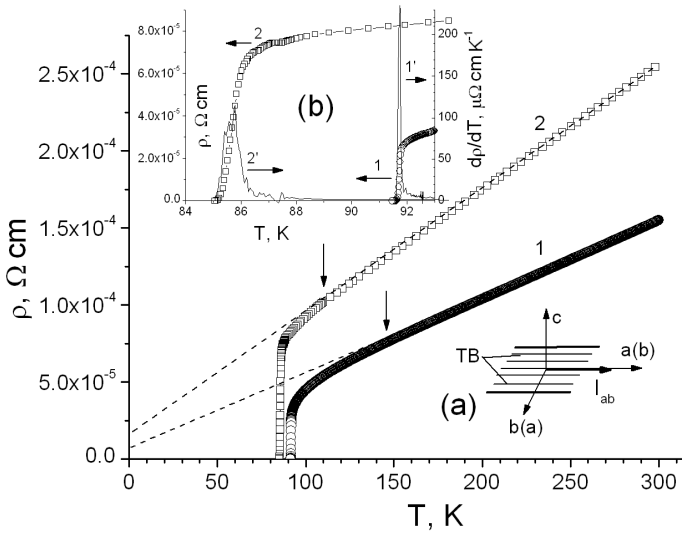

Fig. 1. Temperature dependence of electro-resistivity $\rho_{ab}(T)$ for the single crystals K1 and K2 — curves 1 and 2, respectively. The diversion points from the linear are indicated in the figure by arrows. Inset (a): schematic representation of the bridges for the resistivity study. Inset (b): transition into superconducting condition for K1 and K2 in $\rho - T$ and $\mathrm{d}\rho_{ab}/\mathrm{d}T - T$ coordinates. The shape of symbols of the curves in the inset is in accordance to the shape of symbols in the figure.

3. Results and discussion

T_c is defined as the critical temperature value, corresponding to the maximum in the $dR_{ab}(T)/dT$ dependence in the *ab*-plane, in the interval of the transition to the superconducting state which is shown in Fig. 1b. The resistivity parameters of the investigated samples are given in Table. It can be seen from Fig. 1 that the $\rho_{ab}(T)$ dependence is metallic for both crystals. When the temperature is reduced below some typical value T^* [4] a deviation of $\rho_{ab}(T)$ from the linear dependence occurs, which is an evidence of the presence of excess conductivity that can be caused by a transition to the PG regime [3, 4, 6–8]. There are two basic scenarios for the pseudogap anomaly in HTSC-systems. According to the first, the appearance of the PG is due to "dielectric" type, short-range order fluctuations, which occur in under-doped compounds (see for example [7]). The second scenario is based on the formation of the Cooper pairs at temperatures substantially higher than the critical $T^* \gg T_c$, with a subsequent establishment of their phase coherence at $T < T_c$ [7, 8].

TABLE

Sample data and material parameters.

Crystal	$\rho_{ab}(300)$ [$\mu\Omega$ cm]	T_c [K]	ΔT_c [K]	T^* [K]	Δ^*_{ab} [meV]	ε_0	$\xi_c(0)$ [Å]
K1	155	91.74	0.3	143	87.3	0.064	1.48
K2	255	85.78	2.5	110	98.1	0.067	1.51

In Fig. 1 it is demonstrated that in the Pr doped sample, the linear section of the $\rho_{ab}(T)$ dependence has an extended width compared with the dopant-free crystal. Additionally, the temperature T^* of the Pr doped sample is displaced, in the section of low temperatures, by more than 30 K. This indicates the relevant narrowing of the temperature interval of excess conductivity existence. Such a behaviour of the $\rho_{ab}(T)$ curves is rather uncommon as doping the YBCO compounds with Pr, with concentrations $z \geq 0.2$, the T^* shift to higher temperatures, was observed by Sandu et al. [3].

The value of $\Delta\sigma$ is usually determined from the equation

$$\Delta\sigma = \sigma - \sigma_0, \tag{1}$$

where $\sigma_0 = \rho_0^{-1} = (A + BT)^{-1}$ is the conductivity value determined by extrapolating the linear section to zero temperature and $\sigma = \rho^{-1}$ is the experimental conductivity in the normal state. The $\Delta\sigma(T)$ dependence is presented in Fig. 2. In wide temperature intervals the temperature dependence is approximated by

$$\Delta\sigma \sim \exp(\Delta^*_{ab}/T), \tag{2}$$

where Δ^*_{ab} is the value determining a certain thermoactivative process through an energetic gap ("pseudo-gap"). The $\Delta\sigma(T)$ exponential dependence was observed

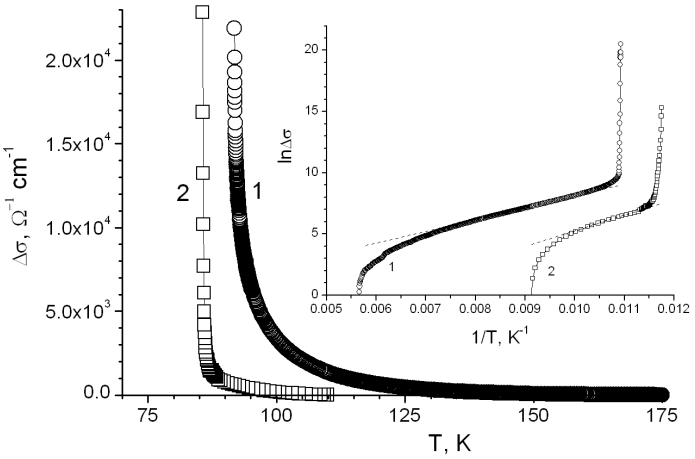

Fig. 2. Plot of excess conductivity temperature dependences in *ab*-plane for K1 and K2 crystals in $\Delta\sigma{-}T$ coordinates. Inset: plot of $\Delta\sigma(T)$ dependences in $\ln(\Delta\sigma){-}1/T$ coordinates. The shape of symbols of the curves is in accordance to the shape of symbols in Fig. 1. The dashed lines in the inset are corresponding to the approximation of the experimental curves from Eq. (3).

previously in YBCO films by Prokofyev et al. [8]. As it was demonstrated by Prokofyev et al. [8], the experimental data approximation is extended by inserting the $(1 - T/T^*)$ factor. The excess conductivity is proportional to the density of superconducting carriers $[n_\mathrm{s} \sim (1 - T/T^*)]$ and inversely proportional to the number of pairs $\sim \exp(-\Delta^*/kT)$, disrupted by the thermal movement. T^* is considered as the middle field temperature of the superconducting transition, when the temperature interval is $T_\mathrm{c} < T < T^*$ (in which there is a pseudogap state). The Δ^*, results for the samples considered are presented in Table.

As is shown from Fig. 2, the $\Delta\sigma$ increases sharply near T_c. According to the Aslamazov–Larkin theoretical model [9], the excess conductivity near T_c is related to the fluctuation pairing of the carriers. This contribution of pairs to the conductivity (2D and 3D), for $T > T_\mathrm{c}$, regarding the 2D and 3D cases is described by the equations

$$\Delta\sigma_{2\mathrm{D}} = \frac{e^2}{16\hbar d}\varepsilon^{-1} \quad \text{and} \quad \Delta\sigma_{3\mathrm{D}} = \frac{e^2}{32\hbar\xi_\mathrm{c}(0)}\varepsilon^{-1/2}, \tag{3}$$

where $\varepsilon = (T - T_\mathrm{c})/T_\mathrm{c}$, e is the electron charge, $\xi_\mathrm{c}(0)$ is the coherence length along the c axis for $T \to 0$ and d is a characteristic size of the two-dimensional layer. At the 2D–3D crossover point we have

$$\xi_\mathrm{c}(0)\varepsilon_0^{-1/2} = d/2. \tag{4}$$

In this case, with the value of ε_0 determined by using published data by Chryssikos et al. [10], on the dependence of the inter-plane distance on δ ($d \approx 11.7$ Å), we can calculate the values of the coherence length $\xi_\mathrm{c}(0)$. Calculations show that by

doping with Pr the value of the coherence length $\xi_c(0)$ changes from $\xi_c(0) = 1.48$ Å for YBCO to $\xi_c(0)_{Pr} = 1.51$ Å for the $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-x}$ crystal with a significant displacement of the 2D–3D crossover point.

Having determined the temperature of transition in the field cooling (FC) regime T_f on a point of a deviation of value $\Delta\sigma$ upwards from linear dependence at lowering of temperature it is possible to estimate the relative extent of the existence of PG and FC regimes of superfluous conductivity as: $t^* = (T^* - T_f)/T_f$ and $t_f = (T_f - T_c)/T_c$. Under slight doping with Pr a relative narrowing of the temperature interval in which the PG regime occurs (from $t^* = 0.530$ to 0.243) is observed. This is synchronous to the relative spreading of the temperature interval in which the FC regime is realized (from $t_f = 0.0158$ to 0.0411) for the K1 and K2 crystals.

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