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Conductivity anisotropy in $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ single crystals with different praseodymium content

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The temperature dependence of longitudinal and transverse conductivity is investigated in $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ single crystals with different praseodymium concentrations. It is shown, that the increasing of praseodymium concentration in samples of $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ leads to enhancement of the localization effects and suppression of the superconducting state. For $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ (in contrast to $YBa_2Cu_3O_{7-\delta}$, compounds) the anisotropy of the normal resistivity $\rho_c/\rho_{ab}(T)$ is described well in the framework of a universal "1/2 law" for thermally activated hopping conductivity.

Измерены температурные зависимости продольной и поперечной проводимости монокристаллов $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ с различным содержанием празеодима. Показано, что увеличение концентрации празеодима в монокристаллах $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ приводит к усилению эффектов локализации и подавлению сверхпроводящего состояния. При этом, в отличие от монокристаллов $YBa_2Cu_3O_{7-\delta}$, анизотропия нормального электросопротивления $\rho_c/\rho_{ab}(T)$ хорошо описывается посредством универсального "закона 1/2" для термоактивационной прыжковой проводимости.

1. Introduction

A general feature of high-T_c superconducting (HTSC) compounds is their pronounced layered structure, which results in substantial anisotropy of a whole range of physical properties, including the electrical conductivity [1–3]. For example, for compounds of $YBa_2Cu_3O_{7-\delta}$ type there is a fundamental difference in the behavior of the resistivity temperature dependence measured in direction of the basal, *ab* plane, $\rho_{ab}(T)$, and along the *c* axis, $\rho_c(T)$. Whereas even a small deviation from stoichiometry in oxygen content leads to a transition from quasimetallic to semiconductor behavior of the $\rho_c(T)$ curves, the $\rho_{ab}(T)$ curves in the high-temperature region, even at an appreciable oxygen deficiencies $\delta > 0.5$, retain a rather wide linear segment which attests to the stability of the normal-carrier scattering intensity [4]. Despite the considerable number of papers devoted to study of the longitudinal and transverse transport in the 1–2–3 system, many aspects of this question remain incompletely clear. For example, a mechanism of resonant tunneling of charge carriers between CuO_2 conducting planes via localized states in the CuO chains was proposed in a theoretical paper [5]. According to [5], the temperature dependence of the anisotropy of $\rho_c/\rho_{ab}(T)$ resistivity should be described by the relation:

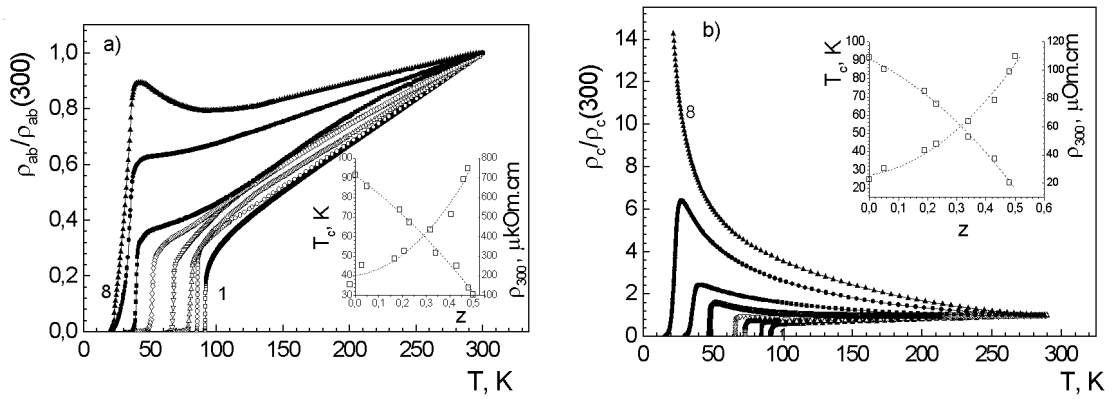

Fig. 1. The temperature dependences of the normalized resistivity (a) — in the *ab*-plane $\rho_{ab}(T)$ and (b) — along *c* axe, $\rho_c(T)$ for K1–K8 single crystals with different praseodymium content *z*: *1* — 0.0, *2* — 0.05, *3* — 0.19, *4* — 0.23, *5* — 0.34, *6* — 0.43, *7* — 0.48, *8* — 0.5. On corresponding inserts are shown dependences of resistance at a room temperature $\rho_{300}(z)$ and critical temperature $T_c(z)$ from praseodymium concentration.

$$\rho_c/\rho_{ab} \sim T\cosh^2(T_0/T), \qquad (1)$$

where T_0 is a certain activation energy of the process. An experimental check of this model was carried out in [3] on single-crystal samples of $YBa_2Cu_3O_{7-\delta}$. However, it was shown that although the theory of [5] agreed qualitatively with experiment, the best description of the experimental data was obtained for exponential dependence of the form:

$$\rho_c/\rho_{ab} \sim \exp(\Delta/T). \qquad (2)$$

A similar expression was justified previously in a theoretical model of [6] that proposed a polaron mechanism for transverse transport in HTSCs.

A characteristic feature of $YBa_2Cu_3O_{7-\delta}$ compound is the relative simplicity of complete or partial substitution of Y by its isoelectronic analogs, making it possible to vary the conducting characteristics to check the adequacy of different theoretical models. A partial substitution of Y by Pr attracts the particular interest in this aspect. The substitution on the one hand, leads to suppression of the crystal superconductivity [2, 7] (unlike the case when Y are substituted by other rare-earth elements), and, on the other hand, allows to remain practically unchanged the lattice parameters and oxygen index of the compound [7]. In particular, study of an influence of Pr impurities on the conductivity anisotropy of such compounds plays an important role not only in elucidating the nature of high-temperature superconductivity (HTSC) but also in determining empirical ways of raising their critical parameters. It should be noted that the existing data on an influence of doping with Pr on the conducting properties of Y–Ba–Cu–O compound remain substantially contradictory till now. Obviously some role in this it is played by the fact that a substantial fraction of the experimental material has been obtained on ceramic and textured samples with different technological prehistory and having a high content of intergranular links. Taking into account the mentioned above, in the present paper we have performed a study of the longitudinal and transverse conductivity of single-crystal samples of the 1–2–3 $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ system with different content of oxygen at replacement ittrium by praseodymium in a wide interval of concentration $0.0 \le z \le 0.5$.

2. Experimental

$Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ single crystals were grown from the flux in a gold crucible by a technology analogous to that used to synthesize $YBa_2Cu_3O_{7-\delta}$ single crystals [1, 2]. To obtain crystals with a partial substitution of Y by Pr, $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$, an amount of Pr_5O_{11} was added to the melting stock in a corresponding atomic ratio. The regimes of growth and oxygen saturation of the $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ crystals were the same as for undoped single crystals [1]. As initial components for growth of the crystals we used the compounds of Y_2O_3, $BaCO_3$, CuO, and Pr_5O_{11}. For the measurements of resistivity we selected single crystals of rectangular form, of length 2.5 mm, width 1.5 mm, and thickness 0.4 mm. Elec-

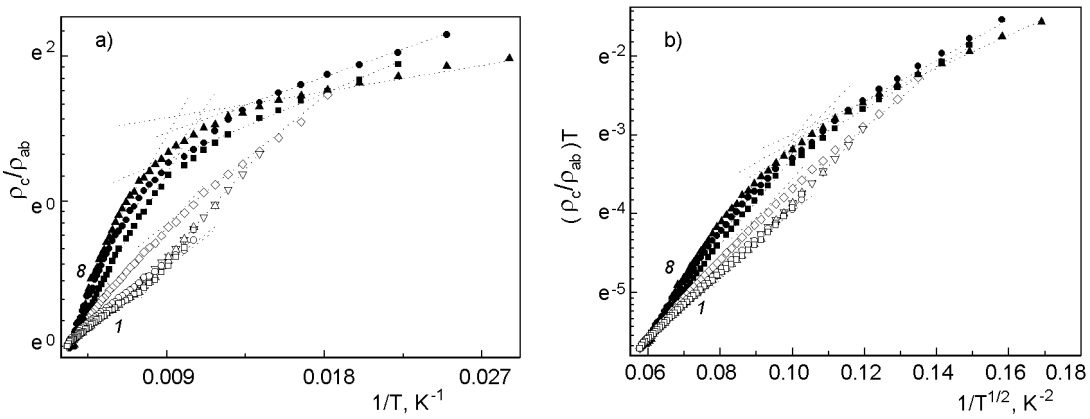

Fig. 2. Temperature dependences of the anisotropy of the resistivity $\rho_c/\rho_{ab}(T)$ in coordinates $\ln(\rho_c/\rho_{ab}) - 1/T$ and $\ln[(\rho_c/\rho_{ab})/T] - 1/T^{-1/2}$. The symbol types are as given in Fig. 1.

trical contacts were created in the standard 8-contact scheme [1]. Temperature was measured by the platinum thermoresistor.

3. Results and discussion

Fig. 1a and 1b show the $\rho(T)/\rho_{300}$ curves measured along and transverse to the basal plane, respectively (dependences of resistivity at a room temperature $\rho_{300}(z)$ and critical temperature $T_c(z)$ from praseodymium concentration are shown on corresponding inserts). Increasing the praseodymium content leads to an increase of the specific resistance approximately in 5 times and a decrease of T_c from ≈ 92 to ≈ 23 K, that qualitatively is in agreement with literary data [7]. It is seen that there exists a fundamental difference in the behavior of curves $\rho_c(T)/\rho_{300}$ and $\rho_{ab}(T)/\rho_{300}$. While an increasing praseodymium concentration leads to pronounced semiconductor behavior of the $\rho_c(T)/\rho_{300}$ curves (Fig. 2), the curves of the resistivity in the basal plane $\rho_{ab}(T)/\rho_{300}$, in the region of relatively high temperatures retain a rather wide (from ≈ 180 to ≈ 20 K) linear segment, which, according to the NAFL theory [4], is a reliable hallmark of the normal state of the system. When the temperature decreases below a certain characteristic value T^* a deviation of $\rho_{ab}(T)$ from the linear dependence occurs, that attests to the appearance of a certain excess conductivity caused by a transition from the pseudogap regime [1, 2].

The second important feature of the temperature dependence of resistivity of the samples with depressed Tc is the significant difference (around ≈ 10.8 K for $z \approx 0.48$ K) of their critical temperatures measured along and transverse to the basal plane. Such an effect was observed previously on single-crystal samples of Bi_2Sr_3Ca–uCu_2O_{8+x} [8] and $YBa_2Cu_3O_{7-\delta}$ [9] with a large deviation from oxygen stoichiometry in resistive measurements of the magnetic susceptibility measurements. The authors of [9] explained this effect by the possible realization of a Friedel transition in the sample [10], which consists in suppression of the transverse superconductivity in a certain temperature region below the critical temperature, $T_f < T < T_c$ (T_f is the Friedel temperature), by means of a specific mechanism of enlargement of annular Josephson vortices in a layered superconductor. It was shown in the theoretical paper [11] that the realization of such a mechanism in a real crystal is possible in the case of a certain breaking of the periodicity of the conducting layers distribution. According to [9] such a situation can occur when a sample contains layers with different T_c separating each other. Evidence in favor of such a scenario is also provided by the results of work [1], in which it is shown that decreasing the oxygen concentration in $YBa_2Cu_3O_{7-\delta}$ single crystals leads to decomposition of the conducting subsystem into several phases with different T_c. The presence of such phases is often not reflected in measurements of resistive transitions to the superconducting state in the *ab* plane owing to the percolational flow of transport current via the phase with the highest T_c.

The temperature curves $\rho_c/\rho_{ab}(T)$ are shown in Fig. 2 in the coordinates $\ln(\rho_c/\rho_{ab}) - 1/T$ and $\ln[(\rho_c/\rho_{ab})/T] - 1/T^{-1/2}$, which corresponds to their description by means of

equation (2) in the first case and by an analytical expression of the form:

$$\rho_c/\rho_{ab} = BT\exp(T_0/T)^{1}\!/_{2}, \qquad (3)$$

in the second case. Here B and T_0 are constants. As we know, equation (3) is characteristic for variable-length hopping conduction — the "1/2 law" [12, 13].

It is seen that decreasing the oxygen concentration leads to significant growth of the anisotropy ρ_c/ρ_{ab} in absolute value. Here it follows from Fig. 2 (a) and (b) that, although Eq.(2) does permit a qualitative description of the experimental dependence at relatively high temperatures, it does this considerably less well than relation (3) does for the hopping conductivity. It is known from the theory that the "1/2 law" is ordinarily interpreted as a manifestation of a Coulomb gap in the energy spectrum of the carriers, that is more characteristic for semiconductor configurations [12]. On the other hand, as it was shown in [13], relation (3) has of a much more universal character and can be used for a wide class of conducting compounds at a sufficiently high degree of structural disorder. In particular, such a situation is realized for the case of granular metals (nanocomposites) — sets of small metallic granules in a dielectric matrix [13]. At the same time, it is known that doping of HTSC cuprates by heterovalent substitution or changing the oxygen concentration leads to decomposition of the system into electrically neutral regions of two types — metallic, with a high carrier density, and dielectric [14]. Here the form of the domains can also be "imposed" by ordered dopants. It is clear that at a sufficiently small size of the metallically conducting inclusions the system can acquire traits which are characteristic for granular metals.

As it is seen from Fig. 2, with increasing praseodymium concentration the slope of the curves $\rho_c/\rho_{ab}(T)$ increases, attesting to an increase of the activation energy from 87–98 K to 374–396 K. It should be also noted that for the curves with depressed $T_c \approx 23 \div 48$ K at temperatures above 128 K a change of slope by more than a factor of four is observed, which in turn attests to a decrease of the activation energy and reflects the presence of phase transitions observed previously in [1] for YBCO single crystals. According to [1], transitions of this type affect the kinetics of charge transport.

4. Conclusions

In summary, analysis of the experimental data obtained allowed us to suggest that an increasing praseodymium concentration in $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ single crystals results in localization of the carriers in the direction of the c axis, and to a change of the interlayer interaction. The temperature dependence of the anisotropy of the resistivity $\rho_c/\rho_{ab}(T)$ for the single crystals studied, unlike $YBa_2Cu_3O_{7-\delta}$, is well described by a universal "1/2 law" for the thermally activated hopping conductivity. This dependence provides evidence that the carriers transport mechanism at perpendicular layers occurs with the help of thermal activated hopping with variable length. The factor 1/2 indicates that the hopping conductivity is 1-dimensional, and /or the Coulomb interaction plays a significant role in the perpendicular transport. Recently, such a behavior was found out in layered organic superconductors in a perpendicular magnetic field [15], that could provide the clue to the question of the incoherent transport across the layers. This effect once more emphasizes the difference between the HTSC cuprates and the Fermi-liquid metals, because the temperature dependence of the resistivity along and across the layers is not the same and differs from the characteristic dependence of the common metals.

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Анізотропія провідності в монокристалах $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ з різним вмістом празеодиму

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Виміряно температурні залежності поздовжньої і поперечної провідності монокристалів $Y_{1-z}Pr_zBa_2Cu_3O_{7-\delta}$ з різним вмістом празеодиму. Показано, що збільшення концентрації празеодиму приводить до посилення ефектів локалізації і пригнічення надпровідного стану. При цьому, на відміну від монокристалів $YBa_2Cu_3O_{7-\delta}$, анізотропія нормального електроопору $\rho_c/\rho_{ab}(T)$ добре описується за допомогою універсального "закону 1/2" для термоактиваційної стрибкової провідності.