

Effect of praseodymium doping on electroresistivity along *c*-axis in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals

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In the present study influence of praseodymium doping on conductivity across (transverse) the basal plane of high-temperature superconducting $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals is investigated. It is determined that increase of praseodymium doping leads to increased localization effects and implementation of the metal — insulator transition $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, which always precedes the superconducting transition. The praseodymium concentration increase also leads to significant displacement of the point of the metal — insulator transition to the low temperature region.

Исследовано влияние допирования празеодимом на проводимость поперек базисной плоскости допированных празеодимом ВТСП-монокристаллов YBaCuO. Установлено, что увеличение степени допирования празеодимом в образцах $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ приводит к усилению эффектов локализации и реализации в системе перехода вида металл — диэлектрик, который всегда предшествует сверхпроводящему переходу. Увеличение концентрации празеодима приводит к существенному смещению точки перехода металл — диэлектрик в область низких температур.

Вплив допування празеодимом на електроопір вздовж с-вісі у монокристалах $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$. *Р.В.Вовк, М.Р.Вовк, О.В.Самойлов.*
Досліджено вплив допування празеодимом на провідність упоперек базисної площини ВТНП-монокристалів YBaCuO. Встановлено, що збільшення ступеня допування празеодимом у зразках $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ приводить до посилення ефектів локалізації та реалізації в системі переходу виду метал — діелектрик, який завжди передує надпровідному переходу. Збільшення концентрації празеодиму приводить до істотного зміщення точки переходу метал — діелектрик в область низьких температур.

1. Introduction

$Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds there is a fundamental difference in the behavior of the temperature dependences of resistivity measured in parallel direction with the basal plane $\rho_{ab}(T)$ and along the axis *c* $\rho_c(T)$ [1–8]. While even a small deviation from oxygen stoichiometry leads to transition from the quasimetallic to semiconductor behavior of the $\rho_c(T)$ curves in the $\rho_{ab}(T)$ dependencies even under considerable oxygen deficiency (i.e. $\delta > 0.5$) at relatively high temperatures a sufficient linear plot remains, indicating stability of the intensity of normal carriers scattering [4]. Qualitatively, the similar behavior is observed in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ [2, 7, 8].

Characteristic feature of high-temperature superconductors (HTSC) is proximity

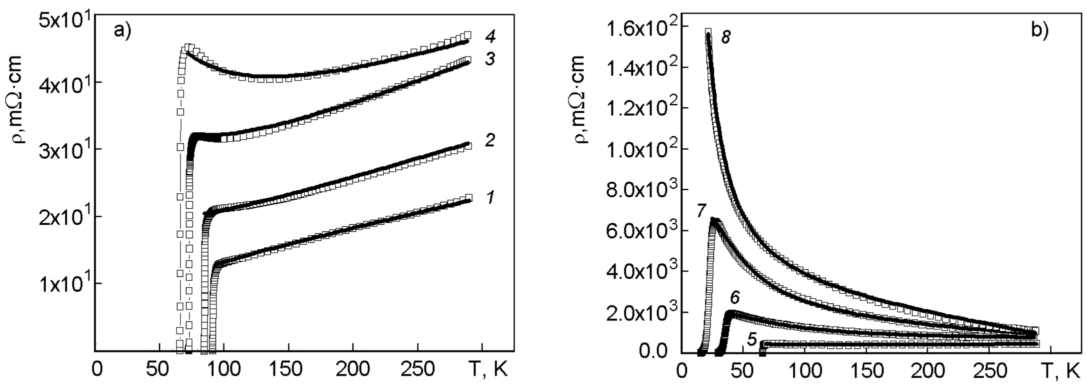

Fig. 1. Plots of $\rho_c(T)$ dependences for $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals for $z = 0.0$, 0.05, 0.19, 0.23, 0.34, 0.43, 0.48, 0.5 — curves *1–8*, respectively.

of the dielectric and superconducting states [2, 3]. This raises questions regarding interference of these states and in particular regarding the role of the localization effects in the superconductivity event in HTSC ? The conductive properties of $YBa_2Cu_3O_{7-\delta}$ compounds could be relatively easily varied by changing oxygen stoichiometry, and by the full or partial substitution of yttrium by isovalent elements. It is established that the substitution of yttrium by rare-earth elements has almost no effect on the conducting properties of the compound in the normal and superconducting state [9]. The only exception is the substitution of yttrium by praseodymium, the so-called "praseodymium anomaly" [2, 3, 10–12]. Adding even a small ($x \approx 0.05$) amount of praseodymium in the samples of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ leads to significant deterioration in their conductive properties [2, 8, 12, 13], which is reflected in the critical temperature (T_c) decrease, the increase of resistivity and the enhancement of the localization effects. When Pr concentration reaches $x \approx 0.6$, the superconductivity in the compound disappears completely [2, 3], and it shifts to insulating state. This transition does not have a significant effect upon the crystal structure and oxygen stoichimetry. This allows us to make smooth changes in the ratio between different types of conductivity and to investigate in detail the electrotransport processes in the experimental samples. In this work, we studied the evolution of conductivity across the basal *ab*-plane in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals with varying concentrations of praseodymium doping in wide concentration range $0 \le x \le 0.5$.

2. Experimental

The single crystals $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ were grown by use of the solution-melt technology [6, 14]. To obtain crystals with partial substitution of yttrium by praseodymium, in the initial lot of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ Pr_5O_{11} was added in the corresponding percentage. Cultivation and oxygenation modes for the crystal growth of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals, were the same as for the undoped crystals [6, 14]. As primary components for growing crystals we used Y_2O_3, $BaCO_3$, CuO and Pr_5O_{11} compounds. The characteristic dimensions of the crystals were $2.5 \times 1.5 \times 0.4$ mm^3 (the smallest size corresponds with the direction along *c*-axis). Resistivity was measured by the octal-contacted method described in [2]. Temperature was measured using a platinum resistance thermometer.

Fig. 1(a) and (b) show the resistivity temperature dependence across the basal *ab*-plane, measured for $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals with different degrees of praseodymium concentration. As the concentration of praseodymium increases, the critical temperature decreases and the resistivity increases, which is consistent with previous studies [10, 11].

Notably when the concentration of praseodymium is in the range of $0.0 \le x \le 0.34$ (Fig. 1(a)), the experimental curves regarding $\rho_c(T)$ dependences remain in a sufficiently wide temperature interval with quasimetallic character. Under subsequent increase of the praseodymium concentration (Fig. 1(b)) these curves are characterized by thermally activated behavior, which indicates increase of the role played by the localization effects.

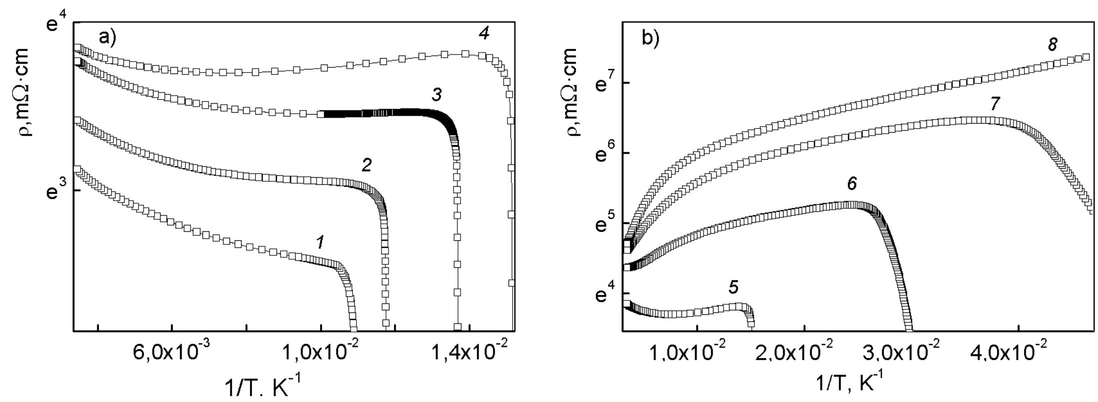

Fig. 2. Plots of resistivity dependences in $\ln S_c(T) - 1/T$ coordinates for different praseodymium content x: a — curves: *1* — 0.0, *2* — 0.05, *3* — 0.19, *4* — 0.23; b — curves: *5* — 0.34, *6* — 0.43, *7* — 0.48, *8* — 0.5.

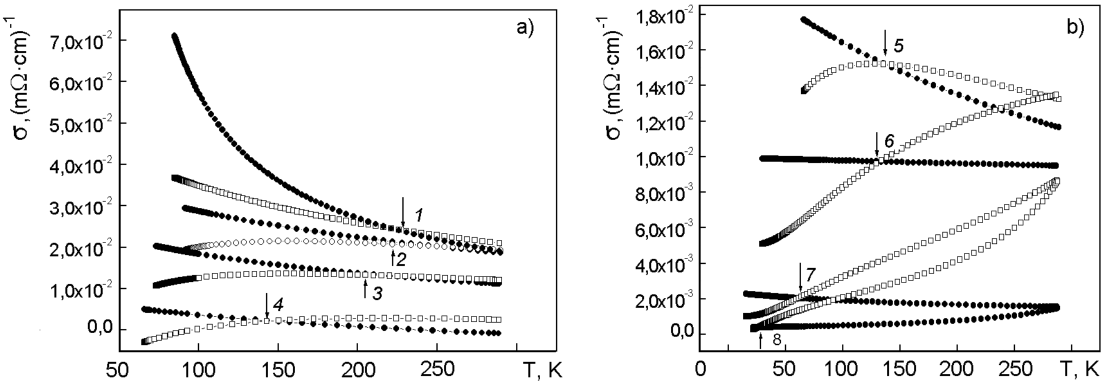

Fig. 3. Temperature dependences $\sigma_{met}(T)$ and $\sigma_{semi}(T)$. The curves numbers are the same as in Fig. 1. Arrows show the metal — insulator transition temperature T_{MI}.

Fig. 2(a) and (b) show the same dependences in $\ln\rho_{ab}$ versus $1/T$ coordinates. It is shown that these experimental curves are straightened in a wide temperature range, which corresponds to the description given by analytic relation:

$$\rho(T) \sim \exp\left(\frac{\Delta}{T}\right), \quad (1)$$

where Δ is the activation energy (over Boltzmann's constant).

When the temperature drops below a characteristic value there commences a systematic deviation of the experimental points from linearity. According to Mott [15] this is indicative of the metal — insulator (MI) "Anderson" type transition in the system. The "Anderson" transition can also occur in materials that are not amorphous, but have a certain degree of disorder [15]. In the compounds of 1–2–3 system the role of this factor can play as disorder of the labile components [9, 16] as praseodymium-doped induced partial clustering of the experimental sample [17].

In a previous study [18], the following equation was proposed for analysis of the experimental curves $\rho_c(T)$:

$$\rho = \frac{\rho_0 + \alpha T}{1 - n[1 - \exp(-\Delta E/2kT)]} - \frac{\beta T_c}{T - T_c} \quad (2)$$

were the first term describes the metal or the semiconductor temperature dependence of resistivity in the normal state and the second term, describes the fluctuation superconductivity that occurs at temperature above the resistive transition to the superconducting state [19, 20]; n and $1-n$ are contributions of the metallic and semiconducting conductivity, respectively. Fluctuation paraconductivity for these experimental curves is analyzed in more detail in the previous study [19].

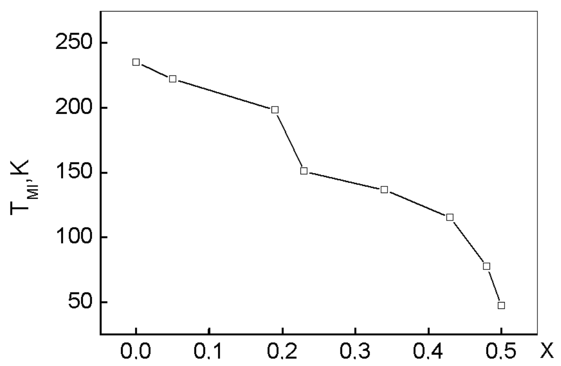

Fig. 4. Plot of T_{MI} dependence on praseodymium content.

Approximation of the experimental data by means of the first term in Eq.(2) is shown in Fig. 1 by the solid curves. Notably all the adjustable parameters used in this analysis are linear formulas of the same kind, which coincides with the praseodymium concentration in our samples. Thus, it can be concluded that in this case Eq.(2) as in [18] is essentially one-parameter.

Using values of the parameters obtained from the analysis of our curves by means of Eq.(2), we have divided according to the previous studies [18] the contributions corresponding to the metal and semiconductor components of conductivity for all the samples. Fig.3(a) and (b) show the temperature dependences $\sigma_{met}(T)$ and $\sigma_{semi}(T)$, calculated by Eq.(3) [18] using the above parameters:

$$\sigma_1 = \frac{1-n}{pho_0 + \alpha T} \text{ and} \quad (3)$$

$$\sigma_2 = \frac{n}{(\rho_0 + \alpha T)\exp(\Delta E/2kT)}.$$

Fig. 3 shows, that despite the fact that with increase of praseodymium concentration the semiconductor component fraction increases, the superconducting transition always occurs after beginning of the inequality $\sigma_{met} > \sigma_{semi}$. We can therefore conclude that in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals, the MI transition always precedes the superconducting transition. Implementation of specific quasiparticle scattering mechanisms in the sample, caused by the presence of structural and kinematic anisotropy in the system [21–25] might play a certain role in the phenomenon. If the temperature at which $\sigma_{met} = \sigma_{semi}(T_{MI})$ is considered as the point of the metal-insulator transition, it can be seen that increasing the praseodymium concentration leads to significant shift of T_{MI} to the low temperatures region (see Fig. 4).

Increasing the degree of praseodymium doping in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals leads to increased localization effects and implementation in the system of the metal — insulator type transition which always precedes the superconducting transition. The praseodymium concentration increase leads to significant shift of the transition point T_{MI} to the lower temperatures, which seems to be associated with increase of the semiconducting segment contribution to conductivity in the experimental samples.

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