Short Notes

Effect of hydrostatic pressure up to 12 kbar on the electrical resistance of $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$ single crystals

G. Khadzhai, A. Matsepulin, and R. Vovk

V. N. Karazin Kharkiv National University, Kharkiv 61022, Ukraine
E-mail: gkhadjai@gmail.com;
rvvovk2017@gmail.com

The effect of high hydrostatic pressure up to 12 kbar on the electrical resistivity in the basal *ab* plane of an optimally doped $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$ single crystal were studied. An inhomogeneity of the sample is found that does not depend on the applied pressure, *P*. The $T_c(P)$ dependence increases nonlinearly with increasing *P*, and the value of the baric derivative, dT_c/dP, decreases. Possible mechanisms of the effect of high pressure on T_c are discussed, taking into account the presence of features in the electronic spectrum of charge carriers.

Keywords: $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals, doping with praseodymium, hydrostatic pressure, phase separation, baric derivatives.

The use of high hydrostatic pressures continues to be one of the most popular techniques for studying the structural and magnetoresistive characteristics of high-temperature superconducting cuprates (HTSC) [1, 2]. Although almost 35 years have passed since the discovery of high-temperature superconductors in 1986 by Bednorz and Müller [3], the microscopic mechanism of this unique physical phenomenon remains unclear. In this aspect, the hydrostatic pressure allows not only to check the adequacy of the currently existing numerous theoretical models [4], but also to establish the most significant parameters of HTSC structures, which determine their physical characteristics in the normal and superconducting states. Among the HTSC cuprates, the most popular for this kind of research are compounds of the $RBa_2Cu_3O_{7-\delta}$ (R = Y or another rare-earth element) system [5, 6]. The critical temperature (T_c) of these compounds, optimally doped with oxygen, is $T_c \approx$ ≈ 90 K [7] and weakly depends on the nature of R. Importantly, $CeBa_2Cu_3O_{7-\delta}$ and $TbBa_2Cu_3O_{7-\delta}$ do not form an orto-structure, $PmBa_2Cu_3O_{7-\delta}$ is radioactive, and $PrBa_2Cu_3O_{7-\delta}$ is not superconductive (the "praseodymium anomaly") [8, 9], despite the presence of an orthorhombic unit cell [10]. Of particular interest presents compounds with a partial substitution of Y for Pr, which leads to a par-

tial suppression of superconductivity [11], and the lattice parameters and oxygen stoichiometry of the compound remain practically unchanged.

Typically in cuprates the dT_c/dP dependence is positive [12], while the $d\ln\rho/dT$ derivative is negative and relatively large [4, 13, 14]. However, the data presented in studies concerning the effect of pressure on the T_c in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds (see, e.g., review [15]) are often contradictory. The registration of both positive and negative values of dT_c/dP, and in some cases, the change of sign of dT_c/dP [15] was reported. Importantly, a significant part of the experimental data was obtained on ceramic, film, and textured samples of very different technological backgrounds [4, 13, 15].

In previous studies [2, 16], we investigated the effect of pressure on the resistive characteristics of low-doped praseodymium ($x \approx 0.05$) single-crystal $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ samples. It was determined that, in contrast to stoichiometric $YBa_2Cu_3O_{7-\delta}$ samples, the application of high pressure to $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ single crystals leads to a double increase in the dT_c/dP value [2, 16]. In these studies, possible mechanisms of the effect of high pressure on T_c were considered, taking into account of features in the electronic spectrum of the charge carriers. In the present study, we
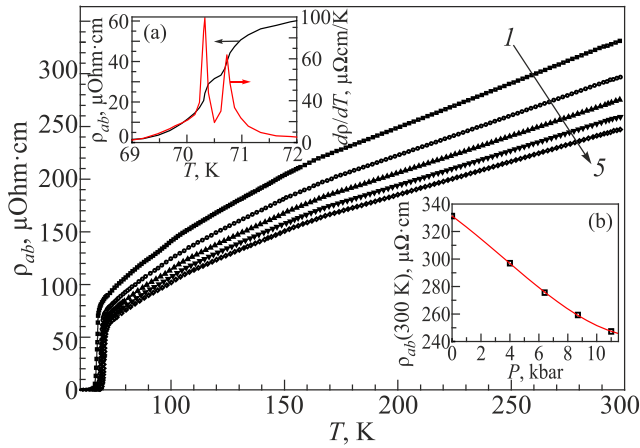
Fig. 1. The electrical resistivity of the $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$ single crystal in the basal plane, $\rho_{ab}(T, P)$, for $P = 0$ (*1*), 4 (*2*), 6.4 (*3*), 8.7 (4), 11 (*5*) kbar. Inset (a): $\rho_{ab}(T, 11$ kbar) and $d\rho_{ab}(T, 11$ kbar)$/dT$ in the superconducting transition region. Inset (b): $\rho_{ab}(300$ K, $P)$.

investigate the effect of hydrostatic pressure on the electrical resistivity in the basal plane of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals with an average concentration of praseodymium $x \approx 0.23$ and a critical temperature $T_c \approx 67$ K.

Figure 1 shows the temperature dependences of the electrical resistivity in the basal plane, $\rho_{ab}(T)$, for the $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$ single crystal measured at different pressures (0, 4, 6.4, 8.7, 11 kbar, see Table 1). At atmospheric pressure, T_c and $\rho_{ab}(300$ K) were ≈ 67 K and ≈ 333 µOhm·cm, respectively. Thus, in comparison with pure single-crystal $YBa_2Cu_3O_{7-\delta}$ samples, the critical temperature decreased by 24 K with a simultaneous increase in $\rho_{ab}(300$ K, 0) by ≈ 83 µOhm·cm, which is generally consistent with the literature data.

Table 1. Characteristics of the conductivity of the $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$ single crystal at various pressures

P, кбар	T_c^{high}, K	T_c^{low}, K	$\Delta = T_c^{\text{high}} - T_c^{\text{low}}$, K	$\rho(300$ K), µOhm·cm
0	67.7	67.2	0.5	333.3
4	69.4	69.0	0.4	298.5
6.4	70.0	69.5	0.5	277.4
8.7	70.4	70.0	0.4	260.4
11	70.7	70.3	0.4	250.1

At present, there are a number of theoretical models for studing of the reasons for the degradation of the superconducting and normal characteristics of $YBa_2Cu_3O_{7-\delta}$ compounds under the influence of praseodymium impurities [15]. The best known among them are the so-called "hole filling model" [17], "pair breaking phenomenon" [18], as well as models assuming the localization of hole carriers and, due to the interaction with praseodymium ions, various mechanisms of rearrangement of band states [15]. A detailed analysis of these phenomena is not presented in our work.

Inset (a) (Fig. 1) for one of the pressures (11 kbar) shows the dependences $\rho_{ab}(T)$ and $d\rho_{ab}(T)/dT$ in the superconducting transition region. It is seen that $\rho_{ab}(T)$ in the region of the superconducting transition has a step, and, accordingly, $d\rho/dT$ demonstrates two maxima, the positions of which correspond to the temperatures of the superconducting transitions. As it was established previously [19, 20], the similar shape of superconducting transitions indicates the presence in the bulk of the experimental sample of several phases with different critical temperatures (T_c^{high} and T_c^{low}), which correspond to the maximum point at each of the peaks. In this case, according to the well-known parabolic dependence [21], each of these phases is characterrized by the corresponding concentration of charge carriers. The behavior of these characteristics indicatives the macroscopic inhomogeneity of the sample; moreover, in measurements of $\rho_{ab}(T)$, only those phases are observed that make up an SC cluster extending from one potential contact to another.

Inset (b) shows the pressure dependence of the room temperature resistance, $\rho_{ab}(300$ K, $P)$. It can be seen that for $P > 6.4$ kbar the linear decrease in $\rho_{ab}(300$ K, $P)$ is replaced by a slower one, in contrast to the data [2], wherein $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ single crystals the linear decrease in $\rho_{ab}(300$ K, $P)$ is replaced by faster for $P > 9$ kbar. This difference may be related to the inhomogeneity of our sample [see Fig. 1, inset (a)] due to enhanced Pr content.

Figure 2 shows the pressure dependences of the superconducting transition temperatures for $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals ($x = 0.23$ — our data, $x = 0.05$ — [2]). The inset shows the pressure dependences of the corresponding derivatives.

It can be seen that the $T_c^{\text{high}}(P)$ and $T_c^{\text{low}}(P)$ curves run almost parallel, i.e., an increase in the applied pressure
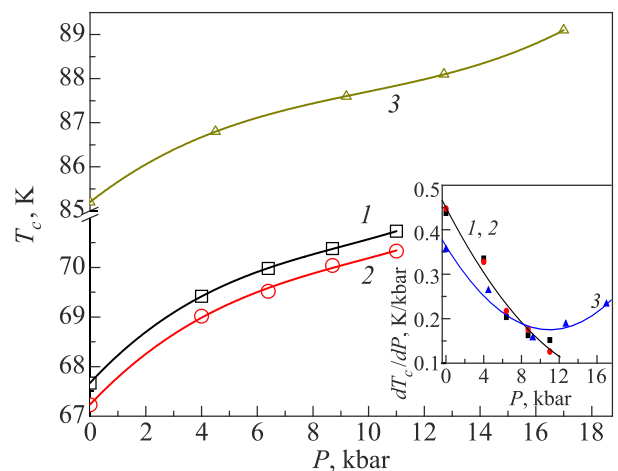

Fig. 2. Baric dependences of the superconducting transitions temperatures: T_c^{high} (*1*), T_c^{low} (*2*), $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ (*3*) [2]. Inset: pressure dependences of derivatives dT_c/dP for $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals ($x = 0.23$ and 0.05, curve numbering is retained).

does not lead to a significant change in the $T_c^{\text{high}} - T_c^{\text{low}}$ difference (see Table 1), which may indicate the preservation of the initial phase separation in our sample.

Notably, the oxygen content here was close to stoichiometric, which should minimize the effect of the redistribution of labile oxygen on the above processes. Indeed, as shown previously [7, 22], the application of high pressure in the case of YBa$_2$Cu$_3$O$_{7-\delta}$ samples of stoichiometric composition, as a rule, does not lead to the occurrence of structural relaxation processes, which usually occur due to the diffusion of labile oxygen in the bulk of the sample. The phase separation under pressure observed in the present study can be due to a change in the size and composition of clusters characterized by different contents of praseodymium [23]. It should be noted that an increase in the praseodymium content in a local volume element of an experimental sample, as a rule, leads to the effect of a diametrically opposite effect of an increase in the oxygen content. An increase in the oxygen concentration leads to an increase in T_c and an improvement in the conducting characteristics of an individual phase [2, 24]. An increase in the praseodymium content contributes to the suppression of conductivity and a decrease in T_c [15, 23]. Thus, it can be assumed that the phase separation observed in the Y$_{1-x}$Pr$_x$Ba$_2$Cu$_3$O$_{7-\delta}$ compound under the action of high pressure, in contrast to the case of pure YBa$_2$Cu$_3$O$_{7-\delta}$ samples, is a more complex and ambiguous process. However, verification of the validity of this assumption requires additional studies of the effect of all-round compression on the critical temperature of Y$_{1-x}$Pr$_x$Ba$_2$Cu$_3$O$_{7-\delta}$ compounds, including a wider range of praseodymium concentrations, as well as using structural measurements on the samples with a higher degree of praseodymium doping.

With pressure increasing, the temperatures of superconducting transitions increase, and in our case ($x = 0.23$) $T_c(P)$ curves are located below the analogous curve for $x = 0.05$ [2], which qualitatively agrees with the data [26] obtained for the Y$_{1-x}$Pr$_x$Ba$_2$Cu$_3$O$_{7-\delta}$ composites.

As follows from the inset in Fig. 2, dT_c / dP for our sample decreases almost linearly with increasing pressure, deviating, however, upward at the highest used pressures. At the same time, for Y$_{0.95}$Pr$_{0.05}$Ba$_2$Cu$_3$O$_{7-\delta}$ [2], the pressure dependence of dT_c / dP passes through a minimum at $P \approx 10$ kbar. Probably, such a minimum can be expected for the studied Y$_{0.77}$Pr$_{0.23}$Ba$_2$Cu$_3$O$_{7-\delta}$ composition, but at higher pressures.

As we have already noted in [16], this behavior of the baric derivatives dT_c / dP can be explained by the traditional use of the well-known McMillan formula for a qualitative analysis of the $T_c(P)$ dependences within the BCS theory [27]:

$$T_c = \frac{\theta_D}{1.45} \exp\left[-\frac{1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)} \right], \quad (1)$$

where θ_D is the Debye temperature, μ^* is the screened Coulomb pseudopotential characterizing the repulsion of electrons, λ is the electron-phonon interaction constant, which depends on the parameters of the electronic and phonon spectrum of the superconductor:

$$\lambda = \frac{N(\varepsilon_F)\langle I^2(\mathbf{k}-\mathbf{k}')\rangle}{M\theta_D^2}, \quad (2)$$

where $N(\varepsilon_F)$ is the density of states at the Fermi level, I is the matrix element of the electron-phonon interaction averaged over the Fermi surface, and M is the mass of the ion.

Under the assumption that upon compression of the sample, along with an increase in the Debye temperature, the matrix element of the electron-phonon interaction also increases [28], the values of $dT_c / dP < 0.2$ K/kbar seem to be quite reasonable. Herewith, it should be noted that for samples with a praseodymium impurity concentration $x > 0.3$, the absolute value of the baric derivative dT_c / dP can reach values greater than 0.6 [15]. In addition, a change in the sign of dT_c / dP was observed in some works. All of the above does not allow us to uniquely interpret the data obtained in the framework of the BCS theory.

At the same time, the relatively weak effect of pressure on the T_c value of samples weakly doped with praseodymium can be explained within the framework of the model assuming the presence of a Van Hove singularity in the spectrum of charge carriers [29, 30], which is characteristic of strongly coupled lattices. As is known, for crystals with high $T_c \approx 90$ K the Fermi level lies in the valley between two peaks of the density of states, while the density of states at the Fermi level $N(E_F)$ significantly depends on the so-called orthorhombic distortion $(a - b)/a$ [29]. An increase in the $(a - b)/a$ ratio leads to an increase in the distance between the peaks of the density of states and, accordingly, to a decrease in $N(E_F)$ and T_c. A decrease in the $(a - b)/a$ ratio leads to the convergence of the peaks of the density of states which leads to an increase in $N(E_F)$ and T_c. Such regularity of the change in T_c was observed when studying the effect of uniaxial compression along the a and b axes on the critical temperature of single crystals with $T_c \approx 90$ K [31]. When a load was applied along the a axis, the critical temperature increased, and when a load was applied along the b axis, it decreased. Under the influence of hydrostatic pressure, the value of the $(a - b)/a$ ratio changes only slightly, since it is determined only by the difference in compression moduli along the a and b axes. Therefore, the change in the critical temperature under the influence of hydrostatic pressure is relatively small.

For crystals with a low $T_c \approx 60$ K, the Fermi level, due to strong doping with substitutional elements, can be shifted from the middle of the band and located away from the peak of the density of states [32]. Therefore, if the value of the critical temperature is primarily determined by the density of electronic states, then under the action of hydrostatic

pressure the Fermi level can shift toward the peak of the density of states, thereby leading to a significant increase in the absolute value of dT_c/dP. However, verification of the validity of this assumption requires additional studies of the effect of pressure on the critical temperature of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds, including a wider range of praseodymium concentrations.

Summarizing the above, we note that the hydrostatic pressure does not affect the morphology of the superconducting cluster in the optimally doped $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$ single crystal. With increasing pressure, $T_c(P)$ increases, deviating downward from the linear course, whereas the baric derivative, dT_c/dP, decreases quasilinearly. Possible mechanisms of the effect of high pressure on T_c are discussed, taking into account the presence of features in the electronic spectrum of charge carriers.

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Вплив гідростатичного тиску до 12 кбар на електричний опір монокристалу $Y_{0,77}Pr_{0,23}Ba_2Cu_3O_{7-\delta}$

G. Khadzhai, A. Matsepulin, R. Vovk

Досліджено вплив високого гідростатичного тиску до 12 кбар на електричний опір в базисній *ab*-площині оптимально допованого монокристалу $Y_{0,77}Pr_{0,23}Ba_2Cu_3O_{7-\delta}$. Виявлено неоднорідність зразка, яка не залежить від прикладеного тиску P. При зростанні P температура надпровідного переходу, T_c, нелінійно збільшується, а величина баричної похідної, dT_c/dP, зменшується. Обговорюються можливі механізми впливу високого тиску на T_c з урахуванням наявності особливостей в електронному спектрі носіїв.

Ключові слова: монокристали YBaCuO, допування празеодимом, гідростатичний тиск, фазове розшарування, баричні похідні.