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Pressure effect on the electrical resistance of $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$ single crystals

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The effect of hydrostatic pressure up to 12 kbar on the electrical resistance in the basal *ab*-plane of optimally oxygen-doped ($\delta < 0.1$) single crystals $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ moderately doped with praseodymium ($x \approx 0.23$) with a critical temperature $T_c \approx 67$ K. Compared to undoped single-crystal $YBa_2Cu_3O_{7-\delta}$, doping with praseodymium led to a decrease in the critical temperature by ≈ 24 K with a simultaneous increase in ρ_{ab} (300 K) by $\approx 130 \mu\Omega\text{cm}$. In the region of the transition to the superconducting state, several clearly pronounced peaks are observed on the $d\rho/dT - T$ curves, which indicates the presence of several phases with different critical temperatures in the sample. The application of high hydrostatic pressure leads to an increase in T_c by about 3 K. This increase slows down with increasing pressure, and the baric derivatives, dT_c/dP , decrease from 0.44 K/kbar at atmospheric pressure to 0.14 K/kbar at 11 kbar. The comparatively weak change in the critical temperature under the action of hydrostatic pressure is due to the relatively small value of the orthorhombic distortion, $(a-b)/a$. The change in the baric derivative dT_c/dP upon all-round compression of the sample is due to the fact that, along with an increase in the Debye temperature, the matrix element of the electron-phonon interaction also increases. 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 carriers.

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

Вплив тиску на електричний опір монокристалів $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$

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Досліджено вплив гідростатичного тиску до 12 кбар на електричний опір в базисній *ab*-площині оптимально допованих киснем ($\delta < 0.1$) монокристалів $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, помірно легованих празеодимом ($x \approx 0.23$) з критичною температурою $T_c \approx 67$ К. Порівняно з нелегованими монокристалічними зразками $YBa_2Cu_3O_{7-\delta}$, легування празеодимом призвело до зменшення критичної температури на ≈ 24 К при одночасному збільшенні ρ_{ab} (300 К) на ≈ 130 мкОм·см. В області переходу в надпровідний стан спостерігається кілька чітко виражених піків на кривих $d\rho/dT - T$, що свідчить про присутність в зразку декількох фаз з різними критичними температурами. Високий гідростатичний тиск призводить до зростання T_c приблизно на 3 К. Це зростання сповільнюється при збільшенні тиску, причому баричні похідні, dT_c/dP , зменшуються від 0.44 К/кбар при атмосферному тиску, до 0.14 К/кбар при 11 кбар. Порівняно слабка зміна критичної температури при впливі гідростатичного тиску обумовлена відносно малою величиною орторомбічної дисторсії, $(a-b)/a$. Зміна баричної похідної dT_c/dP при всебічному стиску зразка пов'язана з тим, що поряд зі зростанням температури Дебая, збільшується і матричний елемент електрон-фононної взаємодії. Можливі механізми впливу високого тиску на T_c обговорюються з урахуванням наявності особливостей в електронному спектрі носіїв.

Ключові слова: монокристали $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, легування празеодимом, гідростатичний тиск, поділ фаз, баричні похідні.

Влияние давления на электросопротивление монокристаллов

$Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$

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Исследовано влияние гидростатического давления до 12 кбар на электрическое сопротивление в базисной ab -плоскости оптимально допированных кислородом ($\delta < 0.1$) монокристаллов $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, умеренно легированных празеодимом ($x \approx 0.23$) с критической температурой $T_c \approx 67$ К. По сравнению с нелегированными монокристаллическими образцами $YBa_2Cu_3O_{7-\delta}$, легирование празеодимом привело к уменьшению критической температуры на ≈ 24 К при одновременном увеличении $\rho_{ab}(300\text{ K})$ на ≈ 130 мкОм·см. В области перехода в сверхпроводящее состояние наблюдается несколько отчетливо выраженных пиков на кривых $dp/dT - T$, что свидетельствует о присутствии в образце нескольких фаз с различными критическими температурами. Приложение высокого гидростатического давления приводит к росту T_c примерно на 3 К. Этот рост замедляется при увеличении давления, причем барические производные, dT_c/dP , уменьшаются от 0.44 К/кбар при атмосферном давлении, до 0.14 К/кбар при 11 кбар. Сравнительное слабое изменение критической температуры при воздействии гидростатического давления обусловлено относительно малой величиной орторомбической дисторсии, $(a-b)/a$. Изменение барической производной dT_c/dP при всестороннем сжатии образца связано с тем, что, наряду с ростом температуры Дебая, увеличивается и матричный элемент электрон-фононного взаимодействия. Возможные механизмы влияния высокого давления на T_c обсуждаются с учетом наличия особенностей в электронном спектре носителей.

Ключевые слова: монокристаллы $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, легирование празеодимом, гидростатическое давление, фазовое разделение, бариновые производные.

Introduction

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]. Despite the fact that 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 still 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 are compounds with a partial substitution of Y for Pr, which, leads to a partial suppression of superconductivity [11], and allows the lattice parameters and oxygen stoichiometry of the compound to remain practically unchanged.

Typically in cuprates the dT_c/dP dependence is positive [12], while the $dlnp/dT$ 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, for example, review [15]) are often contradictory. The registration of both positive and negative values of dT_c/dP were reported, and in some cases, the change of sign of dT_c/dP [15]. Importantly, a significant part of the experimental data was obtained on ceramic, film and textured samples of very different

technological background [4, 13, 15]. In our previous studies [2, 16], we investigated the effect of pressure on the resistive characteristics of low-doped praseodymium ($x \approx 0.05$) single-crystal samples $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$. 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 value of dT_c/dP [2,16]. In these studies possible mechanisms of the effect of high pressure on T_c , taking into account the presence of features in the electronic spectrum of the carriers were considered [2,16]. In the present study we 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 ($x \approx 0.23$) concentration of praseodymium and a critical temperature $T_c \approx 67$ K.

Results and discussion

Figure 1 shows the temperature dependences of the electrical resistivity in the basal plane, $\rho_{ab}(T)$, of the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal measured at different pressures. Inset (a) shows the resistive transitions to the superconducting state in coordinates $dp/dT - T$. As follows from Fig. 1, the values of T_c and $\rho_{ab}(300\text{ K})$ at atmospheric pressure were 67 K and 331 $\mu\text{Ohm}\cdot\text{cm}$, respectively. Thus, in comparison with undoped single-crystal $YBa_2Cu_3O_{7-\delta}$ samples [16*], the critical temperature decreased by 24 K with a simultaneous increase in $\rho_{ab}(300\text{ K})$ by ≈ 130 $\mu\text{Ohm}\cdot\text{cm}$, which generally agrees with the literature [8,15]. At present, there are a number of theoretical models devoted to the study 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” [18], “pair breaking phenomena” [19], 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].

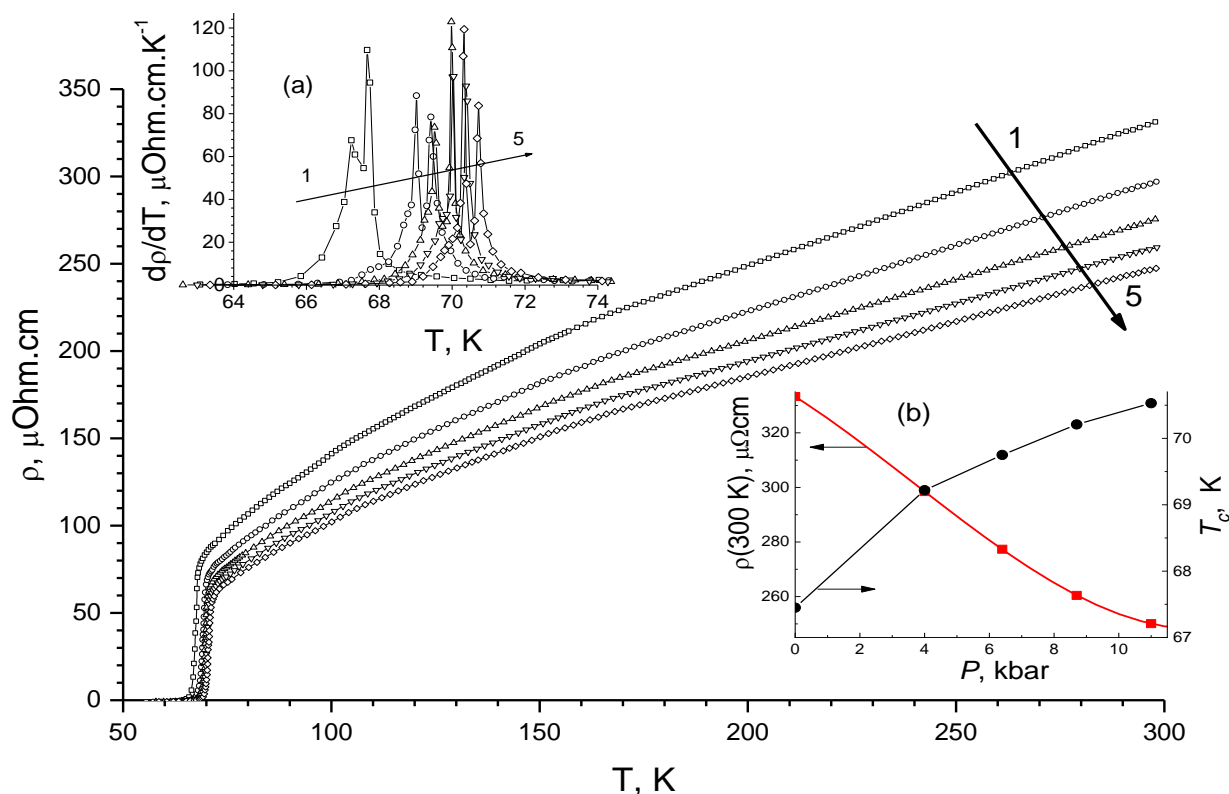


Fig. 1. Temperature dependences of the electrical resistivity in the basal plane, $\rho_{ab}(T)$, of the $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$ single crystal measured at pressures 0; 4.1; 6.4; 8.7; 11 kbar - curves 1-5, respectively. Inset (a): resistive transitions to the superconducting state in coordinates $d\rho/dT - T$. Inset (b): pressure dependences of T_c and $\rho_{ab}(300\text{ K})$.

As can be seen from inset (a), on the $d\rho/dT - T$ coordinates in the region of the transition to the superconducting state, there are several clearly pronounced peaks corresponding to the steps in the corresponding dependences shown in Fig. 1. As it was established previously [20, 21], the similar shape of superconducting transitions indicates the presence in the bulk of the experimental sample of several phases with different critical temperatures (T_{c1} и T_{c2}), which, in turn, correspond to the maximum point at each of the peaks. In this case, according to the well-known parabolic dependence [22], each of these phases is characterized by the corresponding concentration of current carriers. As follows from inset (a), an increase in the applied pressure leads to some change in the height and shape of the steps, as well as a shift in temperature of the maximum points. This, can indicate a significant change in the paths of the transport current due to a change in the size and composition of clusters with different T_c . For $YBa_2Cu_3O_{7-\delta}$ samples of nonstoichiometric oxygen composition, such phenomena can be observed due to the implementation of the ascending diffusion process in the system [23]. As it can be seen from inset (a), an increase in the applied pressure leads to a significant change in the difference ($T_{c1}-T_{c2}$), which may indicate the retention 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, 24], the application of high pressure in the case of $YBa_2Cu_3O_{7-\delta}$ 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. Apparently, 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 [25]. 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. While an increase in the oxygen concentration leads to an increase in T_c and an improvement in the conducting characteristics of an individual phase [23,26], an increase in the praseodymium content contributes to the suppression of conductivity and a decrease in T_c [15,25]. Thus, it can be assumed that the phase separation observed in the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compound under the action of high pressure, in contrast to the case of pure $YBa_2Cu_3O_{7-\delta}$ 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 $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds, including a wider range of praseodymium concentrations, as well as using structural measurements on the samples with a higher degree of praseodymium doping.

As follows from inset (b) for our sample, dT_c/dP decreases from 0.44 K/kbar near atmospheric pressure to 0.14 K/kbar at 11 kbar, which is slightly less than for the sample with $x \approx 0.3$ [15], but more than for the pure sample $YBa_2Cu_3O_{7-\delta}$ [7] and the $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ sample [2,16] As we have already noted previously [16], such a value of the baric derivative dT_c/dP can be explained by the traditional use of the well-known Macmillan formula for a qualitative analysis of the $T_c(P)$ dependences [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, in turn, depends on the parameters of the electronic and phonon spectrum of the superconductor:

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

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 $dT_c/dP < 0.2$ K/kbar seem to be quite reasonable. Herewith, however, 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, as noted above, 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 $N(\varepsilon_F)$ 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 $N(\varepsilon_F)$ and T_c . A decrease in the ratio $(a-b)/a$ leads to the convergence of the peaks of the density of states which leads to an increase in $N(\varepsilon_F)$ and T_c . Such a 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 ratio $(a-b)/a$ 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 . Some role in this case can play the specific mechanisms of quasiparticle interaction [33-35] and relaxation of a defective ensemble, which we discussed in more detail in [36]. 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.

Conclusions

Summarizing the above, we note that hydrostatic pressure does not affect the morphology of a superconducting cluster in a praseodymium-doped $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$ single crystal. It was found that, in contrast to the pure $YBa_2Cu_3O_{7-\delta}$ samples with the optimal oxygen content, the application of high pressure leads to a triple increase in the value of the baric derivative dT_c/dP . Possible mechanisms of the effect of high pressure on T_c are discussed, taking into account the peculiarities in the electronic spectrum of charge carriers.

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