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EFFECTS OF HIGHT HYDROSTATIC PRESSURE ON DIFFERENT TYPES OF CONDUCTIVITY OF YBaCuO SINGLE CRYSTALS WITH A GIVEN TOPOLOGY OF PLANAR DEFECTS

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The effect of high hydrostatic pressures of up to 10 kbar on the basal ab-plane conductivity of $YBa_2Cu_3O_{7-\delta}$ single crystals with unidirectional twin boundaries is investigated. We show that application of a high pressure leads to a substantial decrease of the pressure derivative of the coherence length $d\xi_c/dP$ while increasing dT_c/dP and a temperature shift of the 2D-3D crossover point. Possible mechanisms of the influence of high pressure on the critical temperature and the coherence length are discussed within the frames of a model assuming the presence of singularities in the charge carriers electron spectrum typical for lattices with strong coupling. The excess conductivity $\Delta\sigma$ (T) in $YBa_2Cu_3O_{7-\delta}$ has been revealed to obey an exponential dependence in the wide temperature range $T_c<T<T^*$. At this, the description of the excess conductivity by the expression $\Delta\sigma \sim (1 - T/T^*) \exp(\Delta^*_{ab}/T)$ can be interpreted in terms of the mean-field theory, where T^* is the mean-field superconducting transition temperature and the pseudogap temperature dependence is satisfactory described within the framework of the BCS-BEC crossover theory. An increase of the applied pressure leads to a narrowing of the temperature range of the realization of the pseudogap regime, thereby expanding the linear temperature dependence of the ab-plane resistivity ρ(T).

KEY WORDS: YBaCuO single crystals, hydrostatic pressure, excess conductivity, crossover, coherence length, fluctuation conductivity, pseudogap state, high-temperature superconductivity, critical temperature

ВПЛИВ ВИСОКОГО ГІДРОСТАТИЧНОГО ТИСКУ НА РІЗНІ ТИПИ ПРОВІДНОСТІ МОНОКРИСТАЛІВ YBaCuO ІЗ ЗАДАНОЮ ТОПОЛОГІЄЮ ПЛОСКИХ ДЕФЕКТІВ

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У роботі досліджено вплив високого гідростатичного тиску до 10 кбар на провідність у базисній ab-площині монокристалічних зразків $YBa_2Cu_3O_{7-\delta}$ з системою односпрямованих двійникових меж. Виявлено, що, додавання високого тиску призводить до деякого зменшення величини баричної похідною $d\xi_c/dP$ при одночасному збільшенні dT_c/dP та зміщення за температурою точки 2D-3D кросовера. Обговорюються можливі механізми впливу високого тиску на критичну температуру і довжину когерентності в обсязі експериментального зразка в рамках моделі, що передбачає наявність сингулярностей в електронному спектрі носіїв заряду, який характерний для решіток з сильним зв'язком. Встановлено, що надлишкова провідність Δσ(T) монокристалів $YBa_2Cu_3O_{7-\delta}$ у широкому інтервалі температур $T_c<T<T^*$ підпорядковується експоненційній температурній залежності. При цьому опис надлишкової провідності за допомогою співвідношення $\Delta\sigma\sim(1-T/T^*) \exp(\Delta^*_{ab}/T)$ може бути інтерпретовано в термінах теорії середнього поля, де T^* представлена, як середньопольова температура надпровідного переходу, а температурна залежність псевдощілини задовільно описується в рамках теорії кросовера БКШ-БЕК. Збільшення тиску призводить до ефекту звуження температурного інтервалу реалізації псевдощілинного режиму, тим самим, розширюючи область лінійної залежності ρ(T) в ab-площині.

КЛЮЧОВІ СЛОВА: монокристали YBaCuO, допування, гідростатичний тиск, надлишкова провідність, кросовер, флуктуаційна провідність, псевдощілинний стан, високотемпературна надпровідність, критична температура

ВЛИЯНИЕ ВЫСОКОГО ГИДРОСТАТИЧЕСКОГО ДАВЛЕНИЯ НА РАЗЛИЧНЫЕ ТИПЫ ПРОВОДИМОСТИ МОНОКРИСТАЛЛОВ YBaCuO С ЗАДАННОЙ ТОПОЛОГИЕЙ ПЛОСКИХ ДЕФЕКТОВ

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В работе исследовано влияние высокого гидростатического давления до 10 кбар на проводимость в базисной ab-плоскости монокристаллических образцов $YBa_2Cu_3O_{7-\delta}$ с системой однонаправленных двойниковых границ. Обнаружено, что, приложение высокого давления приводит к некоторому уменьшению величины барической производной $d\xi_c/dP$ при одновременном увеличении dT_c/dP и смещению по температуре точки 2D-3D кроссовера. Обсуждаются возможные механизмы влияния высокого давления на критическую температуру и длину когерентности в объеме экспериментального образца в рамках модели, предполагающей наличие сингулярностей в электронном спектре носителей заряда, который характерен для решеток с сильной связью. Установлено, что избыточная проводимость $\Delta\sigma(T)$ монокристаллов $YBa_2Cu_3O_{7-\delta}$ в широком интервале температур $T_c<T<T^*$ подчиняется экспоненциальной температурной зависимости. При этом описание избыточной проводимости с помощью соотношения $\Delta\sigma \sim (1-T/T^*)\exp(\Delta^*_{ab}/T)$ может быть интерпретировано в терминах теории среднего поля, где T^* представлена, как среднеполевая температура сверхпроводящего перехода, а температурная зависимость псевдощели удовлетворительно описывается в рамках теории кроссовера БКШ-БЭК. Увеличение прилагаемого давления приводит к эффекту сужение температурного интервала реализации псевдощелевого режима, тем самым, расширяя область линейной зависимости $\rho(T)$ в ab-плоскости.

КЛЮЧЕВЫЕ СЛОВА: монокристаллы YBaCuO, допирование, гидростатическое давление, избыточная проводимость, кроссовер, флуктуационная проводимость, псевдощелевое состояние, ввысокотемпературная сверхпроводимость, критическая температура

In the absence of a full microscopic theory regarding the high-temperature superconductivity (HTSC) [1-3], the use of high pressure [4-7] remains an important tool for examining the adequacy of numerous theoretical models and constructing new empirical ways for improving the critical parameters [6,7]of high – T_c materials. In this aspect, compounds of the so-called 1-2-3 system ($YBa_2Cu_3O_{7-\delta}$) are most promising materials to study. This is caused by several reasons. Compounds of the 1-2-3 system have a rather high critical temperature (T_c) allowing for measurements at temperatures above the nitrogen liquefaction temperature [8]. Relatively easy to obtain single crystal [9] alloy [10]and samples large enough. Electrotransport characteristics of these compounds can be easily varied by changing the oxygen content [11-14] and total [15-17]or partial [18-23] replacement of components. Characteristic feature is the presence of compounds YBaCuO planar defects in them - twin boundaries (TB). TB result from tetra-ortho ferroelectric transition at a saturation of the samples to the stoichiometric oxygen content [24-26]. The presence of TB often creates additional difficulties in the study of power, heat and mass transfer due to the complexity highlight the contribution of these planar defects.

Given the motivation above, the aim of this work investigate the effect of pressure on the resistive characteristics of YBa2Cu3O7−δ single crystals, with the geometry of the transport current applied parallel to TBs, that allows us to minimize the effects of scattering at TBs [27]. According to the present-day views it is this unusual phenomenon which alongside with the actuation paraconductivity [2,3], metal-insulator transitions [31,32] and pseudogap anomalies [28-30] is the key to understanding the nature of HTSC.

EXPERIMENTAL METHODS

The $YBa_2Cu_3O_{7-\delta}$ single crystals were grown by the solution-melt technique in a gold crucible as detailed elsewhere [33]. For resistive measurements, crystals of a rectangular shape with the dimensions 3×0.5×0.03 mm3 were selected. The smallest crystal dimension corresponds to the c-axis. The electrical contacts to the samples were formed in the standard 4-probe geometry by applying a silver paste on the crystal surface followed by the attachment of silver leads of 0.05 mm diameter and a three-hour annealing in an oxygen atmosphere at 200ºC. Such a procedure allowed us to obtain a contact transient resistance of less than 1 Ω and to conduct resistive measurements at transport currents of up to 10 mA in the ab-plane.

As is well known, when YBCO compounds are saturated with oxygen, a tetra-ortho structural transformation occurs. This results in crystal twinning which minimizes its elastic energy. To obtain samples with unidirected twins, a bridge of 0.2 mm in width and a distance between the voltage leads of 0.3 mm has been cut out. In doing so, the experimental geometry was chosen such that the electrical current vector I was directed parallel to the twinning plane. The hydrostatic pressure was created in a cylinder-piston pressure multiplier [34]. The pressure value was monitored with a manganin pressure gauge, while the temperature was measured with a copper-constantan thermocouple mounted on the outer surface of the chamber at the sample position level.

RESULTS AND DISCUSSION

Fig. 1 shows the temperature dependence of the basal-plane resistivity $\rho_{ab}(T)$ in the $YBa_2Cu_3O_{7-\delta}$ single crystal for a series of pressures. As shown in Fig. 1, the values of T_c and $\rho_{ab}(300)$ at atmospheric pressure are 91.08K and 98.7 μΩcm, respectively. As it is seen in Fig. 1 and its insets, with increasing applied pressure the resistivity increases and the critical temperature rises with a rate dT_c/dP=0,08 K/kbar, which is consistent with literature data for YBaCuO samples of stoichiometric composition [4,6,7].

In general, the pressure derivative value dT_c/dP can be analyzed relying upon the traditional use of the McMillan formula [35,36] for the $T_c(P)$ dependence, viz.,

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

where θ_D is the Debye temperature, and μ^* is the screened Coulomb pseudopotential describing the electron repulsion. λ is the electron–phonon interaction which, in turn, depends on the parameters of the electron and phonon spectra of the superconductor

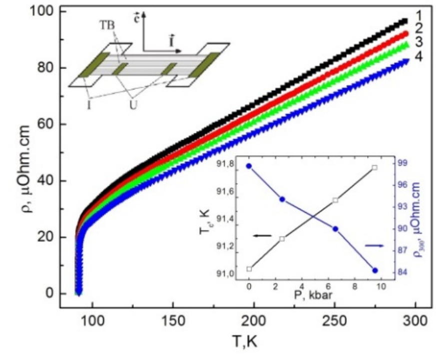

Fig.1. Temperature dependences of the basal-plane electrical resistivity ρ_{ab} (T) of the $YBa_2Cu_3O_{7-\delta}$ single crystal for the series of pressures
1 – 0, 2 – 2.5; 3 – 6.51; 4 – 9.5 kbar. Upper inset: Experimental geometry. Lower inset: Pressure dependence of the critical temperature (left axis) and the resistivity at 300 K (right axis).

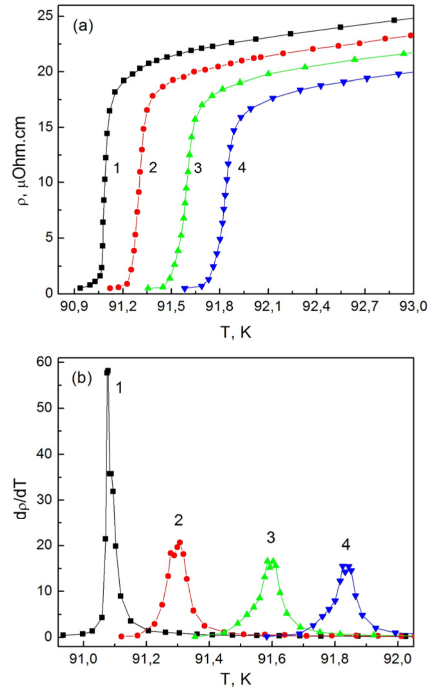

Fig.2. Resistive transitions to the superconducting state (a) and (b) their temperature derivatives.

$$\lambda = \frac{N(\varepsilon_F) < I^2(\vec{k} - \vec{k}^{'}) >}{M\theta_D{}^2}, \tag{2}$$

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 ion mass.

The Fig. 2 shows the resistive transitions to the superconducting state in dρ/dT – T and ρ - T coordinates for a series of pressures. One can distinguish several peaks (Fig. 2b) corresponding to the steps in Fig. 2a. As it has been revealed in [37,38], such a form of the superconducting transition attests to the presence of several phases with different critical temperatures T_{c1} and T_{c2} in the sample volume. These temperatures are defined as those corresponding to the maxima of both peaks. At this, according to the known parabolic law [39], each of these phases is characterized by the respective concentration of the charge carriers.

As follows from Fig. 2a, the increase of the applied pressure leads to some broadening of the superconducting transition and to the change of the height and the shape of the steps, as well as to the temperature upshift of the maxima points. This, in turn, can attest to a substantial modification of the current passes due to the changes in the sizes and the composition of the clusters with different T_c. In the case of non-doped $YBa_2Cu_3O_{7-\delta}$ of oxygen nonstoichiometric composition, phenomena of this kind can be observed as a consequence of the ascending diffusion process [5,38].

As it is seen from Fig. 2a, the increase of the applied pressure leads to an increase of the difference (T_{c1}–T_{c2}), which is indicative of a phase segregation in the sample. At the same time, the oxygen concentration in the sample is close to the stoichiometric content, that should minimize the effect of the labile oxygen redistribution on the aforementioned processes. Indeed, as it was shown in [4-7,40], application of a high pressure in the case of nonstoichiometric $YBa_2Cu_3O_{7-\delta}$ does not, as a rule, initiate structural relaxation processes which usually takes place in consequence of the diffusion of the labile oxygen in the sample volume.

The application of pressure also leads to expansion of the linear portion 10 K depending ρ_{ab}(T) at high temperatures. The latter appears to reduce the magnitude of the temperature T^* at which the systematic deviation of the experimental points down from a linear function. According to modern concepts, the T^* corresponds to the pseudogap opening temperature [2,28], as will be discussed in more detail below.

The sublinear decrease of ρ_{ab}(T) observed at $T<T^*$ attests to the appearance of the so-called excess conductivity, Δσ, in the crystal. The temperature dependence of the excess conductivity is usually determined as

$$\Delta\sigma = \sigma - \sigma_0, \tag{3}$$

where $\sigma_0=\rho_0^{-1}=(A+BT)^{-1}$ is the conductivity determined by interpolating the linear section of ρ(T) to zero temperature and $\sigma=\rho^{-1}$ is the experimental value of the conductivity in the normal state.

The experimental dependence Δσ(T) thus obtained at atmospheric pressure is shown in the inset to Fig. 1 in lnΔσ - 1/T, representation. One sees that in a rather wide temperature range the curve can be fitted to a straight line, that corresponds to its description by an exponential dependence of the form

$$\Delta\sigma \sim \exp(\Delta^*_{ab} / T), \tag{4}$$

where Δ^*_{ab} is the value determining some thermoactivated process over an energy gap — the “pseudogap”.

At present, the most argued-for scenarios of the realization of the pseudogap state in HTSC cuprates refer to the so-called conception of uncorrelated pairs [2,41], as well as various models of dielectric fluctuations [28]. Among the theoretical works standing up for the former viewpoint one should mention the crossover theory from the BCS mechanism to the Bose–Einstein condensation mechanism (BEC) [41]. Specifically, within this BCS–BEC crossover theory obtained were the pseudogap temperature dependences for the cases of weak and strong coupling. In the general form these dependences read

$$\Delta(T)=\Delta(0)-\Delta(0)\sqrt{\frac{\pi}{2}}\sqrt{\frac{T}{\Delta(0)}}\exp\left[-\frac{\Delta(0)}{T}\right]\times\left[1+erf\left(\sqrt{\frac{\sqrt{x_0^2+1}-1}{T/\Delta(0)}}\right)\right], \tag{5}$$

where $x_0 = \mu/\Delta(0)$ with μ being the chemical potential of the system of carriers and Δ(0) the energy gap at T =0, while erf(x) is the error function.

In the limiting case $x_0 \rightarrow \infty$ (weak coupling) expression (5) acquires the form
which is well known in the BCS theory. In the limiting case of strong coupling in the 3D regime ($x_0 < -1$) equation (5)

$$\Delta(T)=\Delta(0)-\Delta(0)\sqrt{2\pi\Delta(0)T}\exp\left[-\frac{\Delta(0)}{T}\right] \tag{6}$$

reduces to

$$\Delta(T)=\Delta(0)-\frac{8}{\sqrt{\pi}}\sqrt{-x_0}\left(\frac{\Delta(0)}{T}\right)^{3/2}\exp\left[-\frac{\sqrt{\mu^2+\Delta^2(0)}}{T}\right]. \tag{7}$$

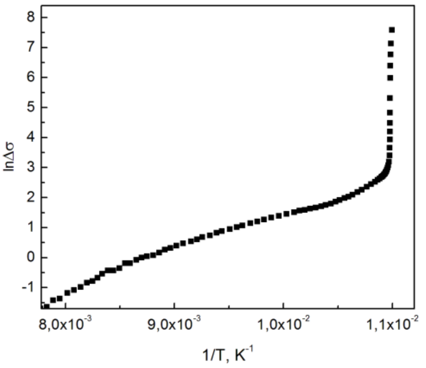

Fig.3. Inverse temperature dependence of the excess conductivity Δσ(1/T) of the sample at atmospheric pressure.

At this, as it was shown in [2, 29, 42], provided the measurement accuracy is high enough, the pseudogap values in a wide temperature range can be deduced from the basal-plane electrical resistivity ρab(T) at temperatures below some characteristic value T^* called the pseudogap opening temperature.

The exponential dependence Δσ(T) was previously observed in YBaCuO samples [43]. As it was shown in [29,42,43], the approximation of the experimental data can be substantially expanded by introducing the factor (1-T/T^*). In this case the excess conductivity turns out proportional to the density of superconducting carriers n_s~(1-T/T^*) and inversely proportional to the number of pairs ~exp(-Δ^*/kT), broken down by the thermal motion

$$\Delta\sigma \sim (1-1/\mathrm{T}^*)\exp(\Delta^*_{ab}/\mathrm{T})\cdot \tag{8}$$

At this, T^* is regarded as the mean-field superconducting transition temperature, while the temperature interval $T_c<T<T^*$, in which the pseudogap state exists, is determined by the rigidity of the order parameter phase. The latter, in turn, depends on the oxygen deficit. In this way, using the methodology proposed in [29,43], from the experimental curve lnΔσ(1/T) one can deduce the temperature dependence Δ^*_{ab}(T) up to T^*.

Fig. 4 presents the temperature dependences of the pseudogap in Δ^*(T)/ Δ_{max} – T/T^* representation for the same series of pressures as in Fig. 1. Here, Δmax is the value of Δ^*on the plateau away from T^*. The dashed lines in Fig. 2 show the dependences Δ^*(T)/ Δ(0) versus T/T^*, calculated by Eqs. (6) and (7) in the mean-field approximation within the framework of the BCS–BEC crossover theory [41] for the crossover parameter μ/Δ(0)=10 (the BCS limit), -2, -5, and -10 (the BEC limit). One sees that as the applied pressure increases, the behavior of the curves transits from Eq. (7) to Eq. (6). This behavior is qualitatively similar to the effect of transformation of the temperature dependence of the pseudogap in YBaCuO samples upon reducing the level of oxygen nonstochiometry [29]. Evidently, the mentioned correlations in the behavior of the curves Δ^*(T) are not occasional. Indeed, as is well known from the literature (see, e.g., [4-7,40]), the application of a high pressure to HTSC samples from the 1-2-3 system, as well as an increase of the oxygen content [29] leads to an improvement of the conducting characteristics, that becomes apparent through a rise of the T_c value and a significant reduction of the resistivity. In this way, given some conditionality of the determination of the value of the pseudogap opening temperature T^* from downturns of the ρ_{ab}(T) curves from the linear dependence, the agreement between the experiment and the theory is satisfactory.

As seen from Fig. 3, in the case of approaching T_c is a sharp increase in the absolute value of the excess conductivity. The excess conductivity near T_c is known to be caused by processes of the fluctuation pairing of the charge carriers. It can be described by the power-law dependence derived in the Lawrence-Doniach model [44]. This model assumes a gradual crossover from the two-dimensional (2D) to the three-dimensional (3D) regime of the fluctuation conductivity upon decreasing the sample temperature

$$\Delta\sigma=\left[\frac{e^2}{16\hbar d}\right]\varepsilon^{-1}\left\{1+J\varepsilon^{-1}\right\}^{-1/2}, \tag{9}$$

where $(T-T^{mf}_c)/T^{mf}_c$ is the reduced temperature with T^{mf}_c being the critical temperature in the mean-field approximation and $J=(2\xi_c(0)/d)^2$ is the interlayer pairing constant with ξ_c being the coherence length along the c-axis and d the thickness of the 2D layer. In the limiting cases, the 3D regime ensues near T_c, when $\xi_c \ll d$ and the interaction is possible in the planes of the conducting layers. In these limiting cases (9) reduces to the known expressions in the Aslamazov-Larkin theory [45]

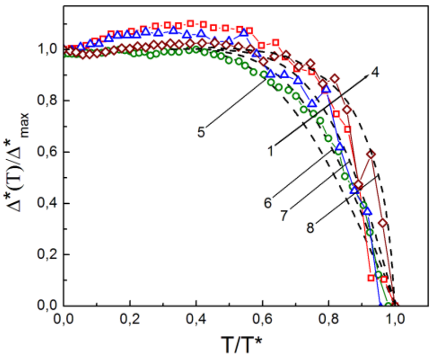

Fig.4. Temperature dependences of the pseudogap in the $YBa_2Cu_3O_{7-\delta}$ single crystal in the reduced coordinates $\Delta^*(T)/\Delta^*_{max}$ – T/T^* (Δ^*max is the value of Δ^* on the plateau away from T*).
The curve numbering corresponds to that in Fig. 1. The dashed lines 5-8 show the dependences $\Delta^*(T)/\Delta(0)$ versus T/T^* calculated according to for the crossover parameter $\mu/\Delta(0)$ =10 (the BCS limit), -2, -5, and -10 (the BEC limit) [41], respectively.

$$\Delta\sigma_{2D} = \frac{e^2}{16\hbar d}\varepsilon^{-1}, \tag{10}$$

$$\Delta\sigma_{3D} = \frac{e^2}{32\hbar\xi_c(0)}\varepsilon^{-1/2} \tag{11}$$

In the case of fitting experimental data a crucial role is played by accurate determination of the value of T^{mf}_c, which substantially affects the slope angle in $\Delta\sigma(\varepsilon)$. Usually, while comparing $\xi_c(0)$, with experimental data, d and T_c in (9), (10), and (11) are fitting parameters [46]. However, when such a method is used, one comes up with considerable discrepancies between theory and experiment. This in turn substantiates the necessity of using a scaling factor, the so-called C-factor, as an additional fitting parameter. This C-factor allows one to fit experimental data to calculated ones and, thereby, to account for possible inhomogeneity of the transport current distribution for each specific sample [46]. In our case for T^{mf}_c we took T_c determined at the derivative maximum in the d $\rho_{ab}/dT(T)$ dependences in the superconducting transition region, as it was proposed in [6] and is shown in the inset (b) to Fig.2.

Fig. 5 displays the temperature dependences $\Delta\sigma(T)$ in $\ln\Delta\sigma(\ln\varepsilon)$ representation. One sees that near T_c these dependences are satisfactory approximated by straight lines with a slope of $\alpha_1\approx$-0.5 corresponding to the exponent −1/2 (11), that attests to the 3D character of the fluctuation conductivity in this temperature range. With a further increase of the temperature the decrease rate of $\Delta\sigma$ speeds up substantially ($\alpha_2\approx$-1). This fact can be viewed as a signature of the dimensionality change in the fluctuation conductivity. As it follows from Eqs. (10) and (11), in the 2D-3D crossover point

$$\varepsilon_0 = 4[\xi_c(0)/d]^2 \tag{12}$$

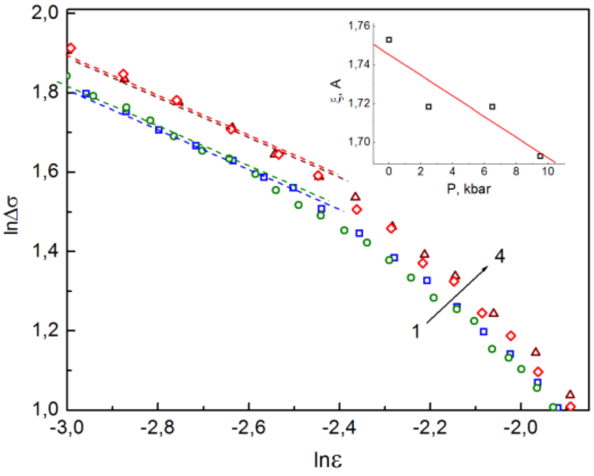

Fig.5. Temperature dependences $\Delta\sigma(T)$ in $\ln\Delta\sigma(\ln\varepsilon)$ representation for a series of pressures.
The curve numbering corresponds to Fig. 1. Inset: Pressure dependence of the coherence length $\xi_c(0)$.

In this case, having determined the value of ε_0 and using the literature data for the dependence of T_c and the interlayer distance on δ [47,48], one can calculate $\xi_c(0)$. As it is seen in the inset to Fig. 2, the value of $\xi_c(0)$ calculated by (12) decreases from 1.75 to 1.69 Å with increasing T_c. This is qualitatively different from the analogous pressure dependences of $\xi_c(0)$for substituent-free YBCO samples, for both optimally doped [6,49] as well as underdoped single crystals [7]. As it was revealed in [6,49], the value of $\xi_c(0)$ for optimally doped crystals is affected by pressure only slightly.

It should also be noted that there is a clear correlation between the behavior of the pressure dependency $\xi_c(P)$ and $T_c(P)$: during the application depressurizing both quantities vary substantially symmetrically - the growth of $T_c(P)$ value $\xi_c(P)$ is reduced and vice versa, which may indicate a change in the same nature of these characteristics. Certain influence in this may have specific mechanisms of the quasiparticle scattering [30,48,50-52], due to the presence in the system of kinematic and structural anisotropy.

CONCLUSION

In summary, the increase of the applied pressure leads to some broadening of the superconducting transition and increases the critical temperature. Such a form of the superconducting transition attests to the presence of several phases with different critical temperatures T_{c1} and T_{c2} in the sample volume. This, can attest to a substantial modification of the current passes due to the changes in the sizes and the composition of the clusters with different T_c.

It is shown that the dependence of the excess conductivity $\Delta\sigma$ (T) is satisfactorily described by the theoretical model Aslamazov-Larkin.

The value of $\xi_c(0)$ decreases from 1.75 to 1.69 Å with increasing T_c. It should also be noted that there is a clear correlation between the behavior of the pressure dependency $\xi_c(P)$ and $T_c(P)$: during the application depressurizing both quantities vary substantially symmetrically – the growth of $T_c(P)$ value $\xi_c(P)$ is reduced and vice versa, which may indicate a change in the same nature of these characteristics.

The application of a high pressure to HTSC samples from the 1-2-3 system, leads to an improvement of the conducting characteristics, which is reflected in an increase in the absolute value of T_c and a significant decrease in resistivity.

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