

Modification by high pressure of fluctuation paraconductivity of underdoped $\text{HoBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystals

S. N. Kamchatnaya,¹ I. L. Goulatis,¹ R. V. Vovk,¹ A. I. Chroneos²

¹*V.N. Karazin Kharkiv National University, 61022, Kharkiv, Kurchatov Av. 31, Kharkov 61108, Ukraine*

²*Faculty of Engineering, Environment and Computing, Coventry University, Priory Street, Coventry CV1 5FB, United Kingdom*

Abstract

In this work, we investigate the effect of high pressure on the conductivity in the basal plane of the high temperature superconducting (HTSC) single crystals $\text{HoBa}_2\text{Cu}_3\text{O}_{7-\delta}$. It is determined that the excess conductivity $\Delta\sigma(T)$ of the $\text{HoBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystals in the temperature interval near the critical temperature (T_c) is described within the framework of the Aslamazov-Larkin theoretical model. It is shown that the evolution of the transverse coherence length $\xi_c(0)$ in the case of application/removal of high pressure is largely determined by the "relaxation" pressure effect during prolonged exposure of the sample under load at room temperature.

Keywords: excess conductivity; hydrostatic pressure; YBaCuO single crystals; high-temperature superconductivity; crossover; pseudogap state.

Introduction

The question about the influence of the dimensionality to the formation of the superconducting state of HTSC cuprates is still open [1-5]. In spite of 30 years of intense experimental and theoretical studies, the microscopic nature of high T_c superconductivity is still unclear [6,7]. The layered structure of HTSC compounds [8,9], along with a short coherence length [10,11] and a large depth of penetration [12], contributes to the emergence of a wide temperature section of excess conductivity [13,14]. It is established that near the critical temperature T_c , the excess conductivity is conditioned by the fluctuation pairing of carriers (fluctuation conductivity - FC) [15], and at higher temperatures $T \gg T_c$, by the so-called pseudo-gap anomaly (PG) [16,17]. According to contemporary concepts [6], these unusual phenomena can serve as a key to understanding the nature of HTSC.

From an experimental viewpoint, the most preferable compounds to conduct studies about electro-transport studies is the so-called 1-2-3 system $\text{ReBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ($\text{Re} = \text{Y}$, or another rare earth ion) [18]. This is mainly due to the fact that the composition of these compounds can be relatively easily varied by changing the oxygen content [19,20] or by substituting elements [21,22] and, thus, with a controlled manner to change their conductive [23,24] and critical [25,26] parameters. Notably, despite the very large number of works devoted to the study of FC [1-5,27,28] and PG [16,17,29] anomalies in HTSC, many aspects of these physical phenomena remain unclear until now, including the question of the impact of structural ordering [30-32] in conducting Cu-O planes, in various mechanisms of conductivity in HTSC.

As is known, the presence of the labile oxygen [32,33] in the $\text{ReBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ($\text{Re} = \text{Y}$, or another rare earth ion) compounds, can contribute to the emergence of a non-equilibrium state, which can occur at high pressures [34,35], “hopping” changes in temperature [36-37] and long-term storage [38-40] and, in turn, may contribute to the process of phase separation [41,42], ascending diffusion [43,44] and the emergence of various kinds of superstructures [45,46]. All these processes have a significant impact on the physical properties of HTSC in the normal and in superconducting states. This is pronounced by the oxygen hypostoichiometric composition of the samples [47,48].

The substitution of yttrium by isovalent rare-earth atoms is important. Particularly, the substitution of yttrium by holmium, having sufficiently high (more than $10 \mu_B$) magnetic moment [49] provides to the compound paramagnetism in the normal state. Nevertheless, as in the case of other rare-earth elements, when implementing the substitution of Y by the paramagnetic ions $\text{Re} = \text{Ho}, \text{Dy}$, the superconducting properties of the optimally oxygen doped $\text{ReBa}_2\text{Cu}_3\text{O}_{7-\delta}$ compounds with $\delta \leq 0.1$, do not change significantly [49]. Apparently this is due to the localization of these ions away from the superconducting planes, which, in turn, prevents the formation of long-range magnetic ordering. At the same time, it is known that in $\text{ReBa}_2\text{Cu}_3\text{O}_{7-\delta}$, the rare earth ion can serve as a sensor sensitive to the local symmetry of its environment and to the charge density distribution, since their change affects to the crystal field, that is forming the electronic structure of such ion [47]. Notably, the yttrium substitution by the holmium can increase in intensity of the redistribution processes in the oxygen subsystem [3,44].

In the absence of a microscopic theory of high-temperature superconductivity, the experimental methods reveal the superconducting parameters, which essentially affect the physical characteristics in the normal and superconducting states. One of the most important methods in this aspect is the use of high pressure [50,51], as it not only allows to clarify the role and influence of the structural features of the system on the formation of the superconducting state, but also gives the

possibility of modeling the conductive characteristics and the critical parameters of the superconductor.

Taking the above under consideration, in the present study we investigated the influence of the structural relaxation induced by high hydrostatic pressure to the FC on $\text{HoBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystals with an oxygen deficiency $\delta \approx 0.35$ and critical temperature $T_c = 67$ K, with a given topology of plane effects (twin boundaries -TB). The use of single-crystal samples allowed us practically, to eliminate the influence on the conductive properties of these structural factors such as intergranular boundaries, dislocations, phase switching, etc, that are often characteristic for films, ceramic and textured samples. Further, the use of bridges with unidirectional TB with geometry $\mathbf{I} \parallel \text{TB}$ helped us to minimize the scattering of the carriers on the TB. Notably, TB are always present in $\text{ReBa}_2\text{Cu}_3\text{O}_{7-\delta}$ compounds under oxygen saturation [52-54] minimizing the elastic energy. Until now, the question regarding the impact of TB on the resistive properties remained open, because of the experimental difficulties encountered in determining their contribution to the electrotransport process.

Experimental methods

The $\text{HoBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystals were grown by the solution-melt method in a gold crucible, similar to the technology of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystal growth [55]. For the oxygen saturation of the crystals to the optimum concentrations $\delta \leq 0.15$, the single crystals were annealed in an oxygen flow at a temperature range 370 - 410 °C for five days. As is known [53], such a procedure is accompanied by the formation of system of twin boundaries (TB) that minimize the elastic energy of the crystal lattice in the tetra-ortho transition. For the resistive measurements, from the same batch of single crystals, we selected a single crystal with dimensions $1.7 \times 1.2 \times 0.2$ mm³ (the smallest dimension is the direction along the c axis), in which there are areas with a unidirectional system of twin boundaries. From the selected single crystal we cut sample by pulsed ultraviolet laser. The pulse duration was 10 μs with a pulse period of 1 ms. The diameter of the laser beam into the cutting area was about 3 μm . The width of the bridge was approximately 0.2 mm and the distance between potential contacts was about 0.3 mm. The twin boundaries inside the bridge were oriented in such a way that the transport current vector \mathbf{I} was parallel to the planes of the twin boundaries ($\mathbf{I} \parallel \text{TB}$). The geometry of the experiment is shown in the insert of Figure 1. To reduce the oxygen content, the samples were annealed for three to five days in an oxygen flow at higher temperatures. The electrical contacts were made from silver wire and were connected to the crystals with a silver paste. The resistivity in the ab -plane was measured at constant current up to 10 mA at the two opposite current directions by the standard four-contact method. Hydrostatic pressure was created in a piston-cylinder autonomous chamber. The value of the pressure was measured by a manganin pressure gauge; the temperature, by a copper-constantan thermocouple mounted in the outer surface of the chamber on the sample position level. To determine the degree of influence of structural relaxation, measurements were carried out after the expiration of a few days after the application-removal pressure, upon completion of the relaxation processes.

Results and discussion

Figure 1 shows the temperature dependence of the resistivity measured at the transport current orientation $\mathbf{I} \parallel c$ ($\rho_{ab}(T)$) and at different pressures. The application of pressure leads to a decrease of the

electrical resistance and to an increase in T_c with $dT_c/dP \approx 0,7 \text{ K.kbar}^{-1}$, which is in qualitative agreement with previous studies [34,50] obtained for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ samples with low oxygen content.

Notably, the decrease in resistivity occurs not only as a result of the hydrostatic pressure, but also during the isobaric exposure of the sample at room temperature immediately after the application of high pressure. For example, the curves in Figure 1 the curves 2 and 3 correspond to the dependences, measured immediately after application of pressure 4.8 kbar and after the isobaric exposure of the sample at the same pressure at room temperature for a week, respectively. It is determined that such exposure leads to an additional decrease of the resistivity by approximately 5%.

A qualitatively similar behavior of the curves $\rho_{ab}(T)$ was observed after removal of the high pressure. Thus, in Figure 1 the curves 1 and 4 show the dependencies, measured before application and immediately after the removal of the pressure. A comparison of these curves shows that the results are dependent upon the exposure time of the sample at room temperature. So, just immediately after the removal of the pressure, the electrical resistance of the sample at room temperature reached a value of about 4% lower than the value measured before the application of pressure and further, it relaxed for about three days until the equilibrium value. After that, the value $\rho_{ab}(290\text{K})$ saturates and the dependence $\rho_{ab}(T)$ (curve 5) is almost identical to the original curve, measured prior to the high-pressure application. This demonstrates the reversibility of the process.

The application of pressure also leads to a substantial (up to 15 K) expansion of the linear section of the $\rho_{ab}(T)$ dependence at high temperatures. The latter is displayed by reducing the value of the so-called pseudogap temperature T^* , at which begins a systematic deviation of the experimental points downwards from the linear dependence. Faster than the linear, is the decrease of the $\rho_{ab}(T)$ value, which is observed in the temperature range $T < T^*$, indicating the appearance of the so-called excess conductivity ($\Delta\sigma$) in the crystal. The temperature dependence of the excess conductivity is usually determined by the equation:

$$\Delta\sigma = \sigma - \sigma_0, \quad (1)$$

where $\sigma_0 = \rho_0^{-1} = (A+BT)^{-1}$, is the conductivity determined by the extrapolation of the linear section to the zero temperature, and $\sigma = \rho^{-1}$, is the experimental value of the conductivity in the normal state. According to contemporary concepts, far away from the T_c , the appearance of $\Delta\sigma$ in HTSC compounds is often associated with the appearance of the so-called pseudogap anomaly [16,17], which is analyzed in more detail in previous work [56]. As is established [57], near the T_c , the excess conductivity is caused due to the processes of fluctuation pairing of charge carriers and can be described by the Lawrence-Doniach theoretical regime, implying the presence of a very smooth crossover from two-dimensional to three-dimensional regime of the fluctuation conductivity by the reduction of the temperature of the sample:

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

where $\varepsilon = (T-T_c^{\text{mf}})/T_c^{\text{mf}}$, is the reduced temperature; T_c^{mf} , is the critical temperature in the mean-field approximation; $J = (2\xi_c(0)/d)^2$, is the interplane coupling constant; ξ_c , is the coherence length along the c axis and d , is the thickness of the two-dimensional layer. In extreme situations (near T_c , when $\xi_c \gg d$, the interaction between the fluctuation Cooper pairs is implemented throughout the entire volume of the superconductor - 3D-regime, or away from T_c , when $\xi_c \ll d$, the interaction is possible only in the

plane of the conductive layers - 2D- regime), the expression (2) is converted into a well-known relations for the three- and two-dimensional cases from the theory Aslamazov-Larkin [15]:

$$\Delta\sigma_{2D} = \frac{e^2}{16\hbar d} \varepsilon^{-1}, \quad (3)$$

$$\Delta\sigma_{3D} = \frac{e^2}{32\hbar\xi_c(0)} \varepsilon^{-1/2}, \quad (4)$$

In the case of comparison with the experimental data it is important to accurately define the value T_c^{mf} , which significantly affects the angle of slope of the $\Delta\sigma(\varepsilon)$. Typically, when comparing with the experimental data $\xi_c(0)$, d and T_c in Equations (2-4) are adjustable parameters [2]. However, when employing such a technique, usually there are deviations between theory and experiment. This, in turn, necessitates the use as an additional adjustable parameter the scaling factor, the so-called C-factor, which allows combining the experimental data with the calculated and thus taken into account the possible spreading of inhomogeneity of the transport current for each sample [2]. In our case, for T_c^{mf} was taken the T_c , defined as indicated above, at the point of maximum on $d\rho_{ab}/dT(T)$ dependences in the regime of the superconducting transition, as suggested in previous work [10].

Figure 2 shows the temperature dependence $\Delta\sigma(T)$ in $\ln\Delta\sigma(\ln\varepsilon)$ coordinates. It is shown that near T_c , these dependences are satisfactorily approximated with the straight lines with the slope angle $\alpha_1 \approx -0.5$, corresponding to the exponent $-1/2$ in Equation (4), indicating the three-dimensional nature of the fluctuating superconductivity in this temperature interval. At higher temperatures the rate of the decrease of $\Delta\sigma$ increases substantially ($\alpha_2 \approx -1$), which can be considered as an indication of the change in the dimension of FC. As it follows from Equations (3) and (4), in the 2D-3D crossover point:

$$\varepsilon_0 = 4[\xi_c(0)/d]^2. \quad (5)$$

In this case, by specifying the value ε_0 and using data from the bibliography on the T_c dependence and the interplanar distance from δ [8,55], we can calculate the value $\xi_c(0)$. As it is shown from Figure 3, the value of $\xi_c(0)$, calculated in accordance with Equation (5), decreases from 4.53 to 4.44 Å by increasing pressure, that is in qualitative agreement with the behavior of the pressure dependences of $\xi_c(0)$ obtained for $YBa_2Cu_3O_{7-\delta}$ single crystals with low oxygen content [58].

It should be noted that the value of the transverse coherence length changes not only in the case of the direct application of high pressure (the so-called "true" pressure effect [58,59]) – section 1-2, but also during the isobaric exposure of the sample at a fixed pressure at room temperature for a week - section 2-3 (the "relaxing" effect [34,35]). Herewith, in the second case, the relative change of $\xi_c(0)$ is significantly larger (from 4.44 to 4.23 Å). In the case of pressure reset, the opposite pattern is observed. In the section 3-4, after the a direct pressure reset, $\xi_c(0)$ increased from 4.23 to 4.42 Å, and subsequently, after further exposure of the sample at atmospheric pressure for three days at room temperature (section 4-5), it recovered to almost the initial value of 4.525 Å. This asymmetry in the evolution of the value $\xi_c(0)$ may be due to several factors.

Firstly, as is known from the literature [58], the structural relaxation, observed in the process of isobaric exposure of $YBa_2Cu_3O_{7-\delta}$ samples at room temperature immediately after the application-removal of the high pressure, can be accompanied by the formation of various types of superstructures, such as pressure-induced lengthening-shortening of oxygen chains in Cu-O planes

or, formation-decay processes of phase clusters with different degrees of oxygen non-stoichiometry [44,58] and, accordingly, different superconducting characteristics.

Such processes are often asymmetric due to the difference in the diffusion path in the direct and reverse processes. Indeed, in order to find a vacant place in the chain, after the application of the load to the oxygen atom, it requires substantially more time than the decay time of such a chain after the load shedding [58]. As an indirect confirmation of this hypothesis, in [34] phenomena of asymmetry relaxation of the critical temperature T_c and of the electrical resistance, the absolute value of which is directly related to the size of such clusters [31,44].

Secondly, the presence in the system of TB, as it was above mentioned, can also lead to the phase separation in the system, since the TB, as defects of higher dimension, could act as powerful current sources of defects of lower dimensions, for example, for the same oxygen vacancies [12 60]. Thus, TB turning out to be the centers of nucleation of the depleted oxygen phase with reduced critical characteristics [60].

As it has been determined previously [42] the high pressure application to HTSC samples with a developed twin structure may facilitate the flow in the system of ascending diffusion processes, when part of the oxygen from the phase with the lower T_c migrates into the phase with the higher critical temperature, and by decreasing pressure, occur the opposite redistribution. Indeed, as it is shown in the inset in Figure 1, the resistive transitions of our sample are characterized by a clearly expressed stepwise form. This, apparently, indicates the presence in the sample of at least two phases, with correspondingly, different critical temperature (T_{c1} and T_{c2}) of the transition to the superconducting state [42].

In Figure 3, curve 1 corresponds to the dependence measured prior the application of the pressure; curve 2 was measured immediately after the application of pressure 4.8 kbar, curve 3, after the sample was retained at room temperature under a pressure of 4.3 kbar for a week; curve 4 was obtained immediately after pressure removal and curve 5, after holding the sample at atmospheric pressure for three days. It can be deduced from this figure, that the exposure of the sample at room temperature in the process of pressure application-removal, in addition to the absolute change in the value of T_c , leads to significant qualitative changes in the width and in the shape of the superconducting transition.

The comparison between curves 2 and 3 shows that after exposure of the sample under pressure for a week, the superconducting transition is broadened considerably (i.e. the difference between the steps corresponding to high and low temperature phases ($T_{c1}-T_{c2}$) increases). In the dependence, measured immediately after removal of the pressure (curve 4), changes only the absolute value of T_c , whereas the width of the transition remains practically unchanged. The comparison of the curves 4 and 5 shows that after the exposure of the sample at atmospheric pressure for three days at room temperature, the width and the shape of the transition is almost fully restored to their original values, indicating the reversibility of the process.

According to previous work [23], the value of the critical temperature of the compound $\text{ReBa}_2\text{Cu}_3\text{O}_{7-\delta}$, is related to the number of holes in the CuO_2 plane, through the universal parabolic relationship:

$$T_c = T_c^{\max} \left[1 - 82.6(n - n_{\text{opt}})^2 \right], \quad (6)$$

where T_c^{\max} , is the maximum critical temperature and $n_{\text{opt}} = 0.25$, is the optimal content of the number of holes on a plane for this compound. The calculations performed based on this relation,

indicate that by increasing the pressure during exposure at room temperature, the number of carriers for the low-temperature phase is reduced by about 3-4%, while regarding the high temperature phase, the reverse process (i.e. increasing the number of holes) occurs.

Finally, the asymmetry in change of $\xi_c(0)$ in the case of pressure application-removal processes, may be partly due to the fact that the time of pressure rising in our experiment was substantially more than the pressure reset time. This is due to the specific of obtaining high pressure in multipliers, piston-cylinder type [61], which is usually generated by a slow (about 30 minutes) indentation of the piston in the working channel by press. At the same time, the pressure reset until the atmospheric pressure is happening rather fast, just in a few seconds. Thus, it is logical to assume that under the relatively slow increase in pressure, the structure is improved (for example, the concentration of vacancies decreases) and the pressure reset leads to the destruction of the order with the formation of excess (non-equilibrium) defects, whose concentration at $P = 0$ relaxes to the initial equilibrium value [42]. Thus, in this case, a certain influence could have the specific mechanisms of quasiparticle scattering [62-64], due to the presence in the system kinetic and structural anisotropy.

Notably, in the case of our sample there is a clear correlation in the behavior of the pressure dependencies $\xi_c(P)$ and $T_c(P)$. With the growth of $T_c(P)$, the value $\xi_c(P)$ decreases, and vice versa, which could indicate that the ratio between these values may be governed by the general theory of superconductivity [65], from which it follows that $\xi_0 \sim hv_F/k_B T_c$.

It is important to note once again that when the pressure is removed and all the relaxation processes are completed, the dependence $\rho_{ab}(T)$ practically coincides with the original curves, measured prior the high pressure application, which indicates the reversibility of the process. Thus, given some conventionality in the definition of the 2D-3D crossover temperature ε_0 , we can assume that the evolution of the transverse coherence length $\xi_c(0)$ in the case of high-pressure application-removal to the non-stoichiometric oxygen samples $\text{HoBa}_2\text{Cu}_3\text{O}_{7-\delta}$, is probably related not only to the change of the lattice parameters, the electron-phonon interaction, the connections between layers, etc. (the so-called “true” pressure effect), but also, to a large extent, is determined by the “relaxation” pressure effect during the prolonged exposure of the sample under load at room temperature. That in its turn is caused by the redistribution of the labile oxygen.

Conclusions

The application of high pressure to the single crystals $\text{HoBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ($\delta \leq 0.35$), leads to a significant expansion of the interval of the linear dependence $\rho_{ab}(T)$, which in turn, in turn, the corresponding narrowing of the temperature section of the realization of the pseudogap regime. Thus, the excess conductivity in the temperature range near the critical T_c is satisfactorily described within the framework of the Aslamazov-Larkin theoretical model. Under pressure the evolution of the FC regime of non-stoichiometric by oxygen $\text{HoBa}_2\text{Cu}_3\text{O}_{7-\delta}$, samples, is apparently determined by two processes: From a general trimerization of the system, due to changes in the relation between ξ_c and d , on the one hand, and the pressure “relaxation” effect conditioned by the redistribution of the labile oxygen, from the other. Herewith, in contrast to the undoped samples $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, the application of high pressure leads to a substantial increase in the value of the pressure derivatives dT_c/dP and $d\xi_c/dP$.

References

1. A. Larkin, A. Varlamov, Theory of fluctuations in superconductors. Oxford University Press, USA (2009). 496 p.
2. T.A. Friedmann, J.P. Rice, J. Giapintzakis, D.M. Ginsberg, Phys. Rev. B **39**, 4258 (1989)
3. A. Solovjov, M. Tkachenko, R. Vovk, A. Chroneos, Physica C **501**, 24 (2014)
4. R.V. Vovk, G.Ya. Khadzhai, I.L. Goulatis, A. Chroneos, Physica B, **436**, 88 (2014)
5. R.V. Vovk, N.R. Vovk, G.Ya. Khadzhai, O.V. Dobrovolskiy, Z.F. Nazyrov, J. Mater. Sci.: Mater. Electron. **26**, 1435 (2015)
6. J. Ashkenazi, J. Supercond. Nov. Magn. **24**, 1281 (2011)
7. E. Babaev, H. Kleinert, Phys. Rev. B **59**, 12083 (1999)
8. G.D. Chryssikos, E.I. Kamitsos, J.A. Kapoutsis, A.P. Patsis, V. Psycharis, A. Koufoudakis, C. Mitros, G. Kallias, E. Gamari-Seale, D. Niarchos, Physica C **254**, 44 (1995)
9. A. Chroneos, I.L. Goulatis, R.V. Vovk, Acta Chim. Sloven. **54**, 179 (2007)
10. L. Mendonca Ferreira *et al.*, Phys. Rev. B **69**, 212505 (2004)
11. R.V. Vovk, G.Ya. Khadzhai, O.V. Dobrovolskiy, Z.F. Nazyrov, A. Chroneos, Physica C **516**, 58 (2015)
12. G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, V.M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994)
13. L. Mendonca Ferreira *et al.* Eur. Phys. J. B **83**, 423 (2011)
14. S.V. Savich, A.V. Samoilov, R.V. Vovk, O.V. Dobrovolskiy, S.N. Kamchatna, Ya.V. Dolgoplova, O.A. Chernovol-Tkachenko, Mod. Phys. Lett. B **30**, 1650034 (2016)
15. L.G. Aslamosov, A.I. Larkin, Phys. Lett. A **26**, 238 (1968)
16. P.A. Lee, N. Nagaosa, X.G. Wen, Rev. Mod. Phys. **78**, 17 (2006)
17. R.V. Vovk, M.A. Obolenskii, A.A. Zavgorodniy, I.L. Goulatis, A. Chroneos, E.V. Biletskiy, J. Alloys Compd. **485**, 121 (2009)
18. M.K. Wu, J.R. Ashburn, C.J. Torng, P.H. Hor, R.L. Meng, L. Gao, Z.J. Huang, Y.Q. Wang, C.W. Chu, Phys. Rev. Lett. **58**, 908 (1987)
19. P. Schleger *et al.*, Physica C **176**, 261 (1991)
20. M.A. Obolenskii, R.V. Vovk, A.V. Bondarenko, N.N. Chebotaev, Low Temp. Phys. **32**, 571 (2006)
21. M. Akhavan, Physica B **321**, 265 (2002)
22. R.V. Vovk, Z.F. Nazyrov, I.L. Goulatis, A. Chroneos, Physica C **485**, 89 (2013)
23. J.L. Tallon, C. Berthard, H. Shaked, R.L. Hitterman, J.D. Jorgensen, Phys. Rev. B **51**, 12911 (1995)
24. R.V. Vovk, N.R. Vovk, G.Ya. Khadzhai, I.L. Goulatis, A. Chroneos, Solid State Commun. **190**, 18 (2014)
25. T. Krekels, H. Zou, G. Van Tendeloo, Physica C **196**, 363 (1992)
26. A.V. Bondarenko, V.A. Shklovskij, M.A. Obolenskii, R.V. Vovk, A.A. Prodan, M. Pissa, D. Niarchos, G. Kallias, Phys. Rev. B **58**, 2445 (1998)
27. H.A. Borges, M.A. Continentino, Solid State Commun. **80**, 197 (1991)
28. R.V. Vovk, N.R. Vovk, G.Ya. Khadzhai, O.V. Dobrovolskiy, Z.F. Nazyrov, Curr. Appl. Phys. **14**, 1779 (2014)

29. R.V. Vovk, N.R. Vovk, G.Ya. Khadzhai, O.V. Dobrovolskiy, Solid State Commun. **204**, 64 (2015)
30. J. Kircher, M. Cardona, A. Zibold *et al.*, Phys. Rev. B. **48**, 9684 (1993)
31. R.V. Vovk, N.R. Vovk, O.V. Dobrovolskiy, J. Low Temp. Phys. **175**, 614 (2014)
32. J.D. Jorgensen, P. Shiyou, P. Lightfoot, H. Shi, A.P. Paulikas, B.M.W. Veal, Physica C **167**, 571 (1990)
33. R.V. Vovk, N.R. Vovk, G.Ya. Khadzhai, O.V. Dobrovolskiy, Z.F. Nazyrov, J. Mater. Sci : Mater. Electron. **25**, 5226 (2014)
34. S. Sadewasser, J.S. Schilling, A.P. Paulikas, B.M. Veal, Phys. Rev. B. **61**, 741 (2000)
35. D.D. Balla, A.V. Bondarenko, R.V. Vovk, M.A. Obolenskii, A.A. Prodan, Low Temp. Phys. **23**, 777 (1997)
36. B.W. Veal, H. You, A.P. Paulikas *et al.*, Phys. Rev. B. **42**, 4770 (1990)
37. M.A. Obolenskii, A.V. Bondarenko, R.V. Vovk, A.A. Prodan, Low Temp. Phys. **23**, 882 (1997)
38. B. Martinez, F. Sandiumenge, S. Pinol, N. Vilalta, J. Fontcuberta, X. Obradors, Appl. Phys. Lett. **66**, 772 (1995)
39. D.A. Lotnyk, R.V. Vovk, M.A. Obolenskii, A.A. Zavgorodniy, J. Kováč, M. Kaňuchová, M. Šefciková, V. Antal, P. Diko, A. Feher, A. Chroneos, J. Low Temp. Phys. **161**, 387 (2010)
40. R.V. Vovk, N.R. Vovk, A.V. Samoilo, I.L. Goulatis, A. Chroneos, Solid State Commun. **170**, 6 (2013)
41. R. Menegotto Costa *et al.*, Physica C **495**, 202 (2013)
42. R.V. Vovk, G.Ya. Khadzhai, Z.F. Nazyrov, I.L. Goulatis, A. Chroneos, Physica B **407**, 4470 (2012)
43. A.M. Kosevich, Ysp. Fyz. N. **114**, 507 (1974)
44. R.V. Vovk, Z.F. Nazyrov, M.A. Obolenskii, I.L. Goulatis, A. Chroneos, V.M. Pinto Simoes, Philos. Mag. **91**, 2291 (2011)
45. H. Lutgemeier, S. Schmenn, P. Meuffels, O. Storz, R. Schollhorn, Ch. Niedermayer, I. Heinmaa, Y. Baikov, Physica C **267**, 191 (1996)
46. R.V. Vovk, Z.F. Nazyrov, M.A. Obolenskii, I.L. Goulatis, A. Chroneos, V.M.P. Simoes, J. Alloys Compd. **509**, 4553 (2011)
47. A. Chroneos *et al.* J. Alloys Compd. **494**, 190 (2010)
48. R.V. Vovk, G.Ya. Khadzhai, O.V. Dobrovolskiy, Z.F. Nazyrov, A. Chroneos, Current Appl. Phys. **15**, 617 (2015)
49. D.M. Ginsberg (ed), Physical properties high temperature superconductors I. – Singapore: World Scientific, 1989.
50. R. Griessen, Phys.Rev. B **36**, 5284 (1987)
51. A.L. Solovjov, M.A. Tkachenko, R.V. Vovk, M.A. Obolenskii, Low. Temp. Phys. **37**, 840 (2011)
52. G. Lacayc, R. Hermann, G. Kaestener, Physica C. **192**, 207 (1992)
53. R.V. Vovk, M.A. Obolenskii, A.A. Zavgorodniy, Z.F. Nazyrov, I.L. Goulatis, V.V. Kruglyak, A. Chroneos, Mod. Phys. Lett. B **25**, 2131 (2011)
54. A.V. Bondarenko, V.A. Shklovskij, R.V. Vovk, M.A. Obolenskii, A.A. Prodan, Low Temp. Phys. **23**, 962 (1997)

55. R.V. Vovk, M.A. Obolenskii, Z.F. Nazyrov, I.L. Goulatis, A. Chroneos, V.M. Pinto Simoes, J. Mater Sci.: Mater. Electron. **23**, 1255 (2012).
56. R.V. Vovk, I.L. Goulatis, A. Chroneos, J. Mater. Sci.: Mater. Electron. **24**, 5127 (2013)
57. W.E. Lawrence, S. Doniach, Proceedings of the 12th International Conference on Low Temperature Physics, Kyoto, Japan, 1970, edited by E. Kanda (Keigaku, Tokyo, 1970), p.361.
58. R.V. Vovk, M.A. Obolenskii, A.A. Zavgorodniy, A.V. Bondarenko, I.L. Goulatis, A.V. Samoilov, A.I. Chroneos, J. Alloys Compd. **453**, 69 (2008)
59. R.V. Vovk, N.R. Vovk, G.Ya. Khadzhai, I.L. Goulatis, A. Chroneos, Physica B **422**, 33 (2013)
60. A.V. Bondarenko, A.A. Prodan, M.A. Obolenskii, R.V. Vovk, T.R. Arouri, Low Temp. Phys. **27**, 339 (2001)

61. N.B. Brandt, E.S. Itskevich, N.Ya. Minina, Physics-Uscpekhi **14**, 438 (1972)
62. R.V. Vovk, N.R. Vovk, O.V. Shekhovtsov, I.L. Goulatis, A. Chroneos, Supercond. Sci. Technol. **26**, 085017 (2013)
63. V.N. Golovach, M.E. Portnoi, Phys. Rev. B **74**, 085321 (2006)
64. R.V. Vovk, G.Ya. Khadzhai, O.V. Dobrovolskiy, Appl. Phys. A **117**, 997 (2014)
65. P.G. Curran, V.V. Khotkevych, S.J. Bending, A.S. Gibbs, S.L. Lee, A.P. Mackenzie, Phys. Rev. B **84**, 104507 (2011)
66. I. N. Adamenko, K.E. Nemchenko, V.I. Tsyganok, A.I. Chervanev, Low Temp. Phys. **20**, 498 (1994)
67. R.V. Vovk, G.Ya. Khadzhai, O.V. Dobrovolskiy, Mod. Phys. Lett. B **28**, 1450245 (2014)
68. P.G. De Gennes, Superconductivity of Metals and Alloys, W.A. Benjamin Inc., New York-Amsterdam (1966).

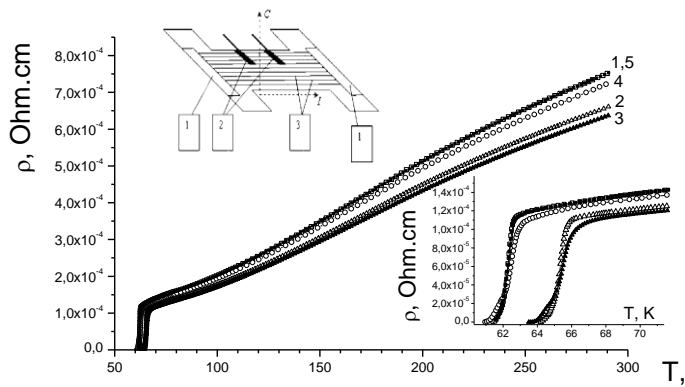


Fig. 1. The $\rho_{ab}(T)$ temperature dependence of the $\text{HoBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystal during the pressure application-removal process. The inset shows the resistive transitions to the superconducting state for the same sample. The numbering of the curves in the inset corresponds to the numbering in the figure.

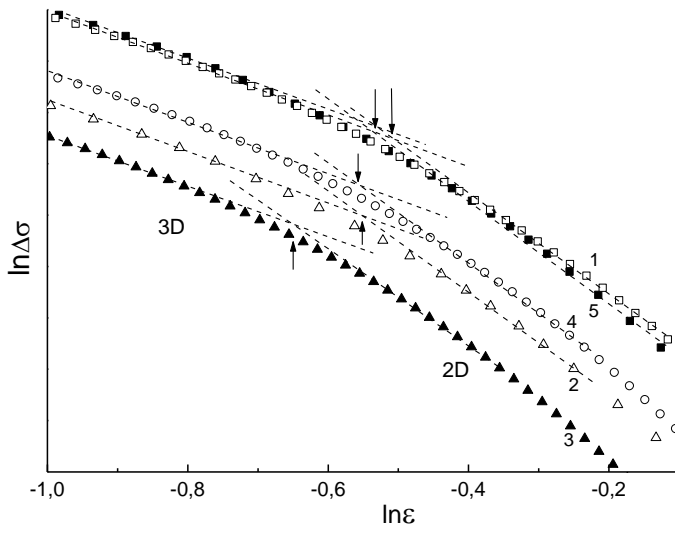


Fig.2. Plot of $\Delta\sigma(T)$ dependence of $\text{HoBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystal in $\ln\Delta\sigma(\ln\varepsilon)$ coordinates. The numbering of curves corresponds to the numbering in Fig. 1.

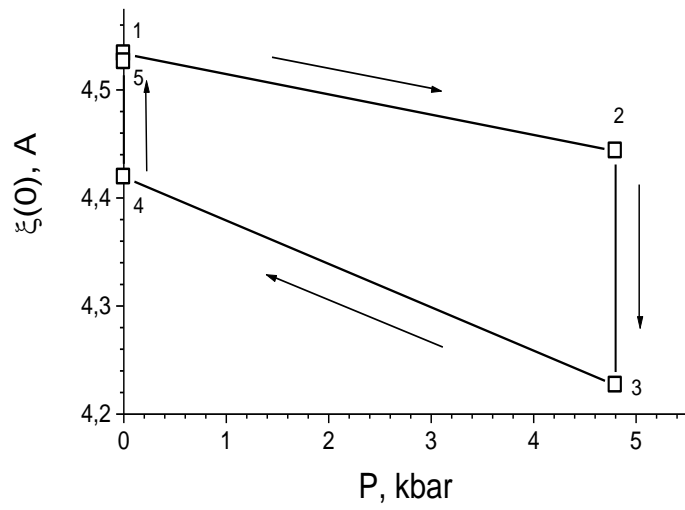


Figure 3. Pressure dependences $\xi_c(0)$ in the pressure application-removal process.