EVOLUTION OF OVER-CONDUCTIVITY OF $YBa_2Cu_3O_{7-\delta}$ SINGLE CRYSTALS UNDER THE EXPOSURE OF IRRADIATION BY HIGH-ENERGY ELECTRONS

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The evolution of the excess conductivity of $YBa_2Cu_3O_{7-\delta}$ single crystals upon electron irradiation is investigated. It was shown that electron irradiation leads to a significant expansion of the temperature range for the existence of excess conductivity, thereby narrowing the region of the linear dependence of $\rho(T)$ in the ***ab*** plane. It was found that the excess conductivity $\Delta\sigma(T)$ of $YBa_2Cu_3O_{7-\delta}$ single crystals in a wide temperature range $T_f<T<T^*$ (T_f – the transition temperature from the PG to the FP mode) is subject to exponential temperature dependence. Moreover, the description of excess conductivity using the relation $\Delta\sigma \sim (1-T/T^*)\exp(\Delta^*_{ab}/T)$ (Δ^*_{ab} – the pseudogap in ***ab***-plane) can be interpreted in terms of the mean-field theory, where T^* is presented as the mean-field temperature of the transition to the PG state, and the temperature dependence of the pseudogap is satisfactorily described in the framework of the BCS-BEC crossover theory. In this case, the value of the transverse coherence length $\xi c(0)$ increases 1.4 times and the 2D-3D crossover point shifts in temperature.

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INTRODUCTION

As is known, a characteristic feature of high-temperature superconducting cuprates (HTSC) is the presence of a broad temperature region of excess conductivity, $\Delta\sigma$, in the temperature dependences of conductivity [1–3]. Near the critical temperature (T_c) $\Delta\sigma$, it is caused by fluctuation corrections to the conductivity, which, as a rule, are well described within the framework of the well-known theoretical models of Aslamazov-Larkin [4], Mackie-Thompson [5] and Lawrence-Doniakh [6] for layered superconducting systems. Far from T_c, at temperatures of 1.5 T_c and above, $\Delta\sigma$ is caused by the so-called pseudogap anomaly (PG), the question of the origin of which is still quite debatable [2, 7, 8]. Currently, as a rule, two main scenarios of the occurrence of PG in HTSC compounds are considered. Its knows as the scenario of "uncorrelated pairs" [2, 3, 8, 9] and several so-called mechanisms of various kinds of "dielectric fluctuations", which are described in sufficient detail in reviews [2, 7, 10].

According to modern concepts, the PG anomaly [2, 3, 7–11] and AF [1, 2, 4–6, 12] are the keys to understanding the microscopic nature of HTSC, which remains unclear [13], despite more than 30-year-old history of intensive theoretical and experimental research.

As shown by numerous experimental studies, conductivity is very sensitive to various kinds of extreme impacts, such as high pressures [14, 15], fast [16, 17] and long-term [18–20] annealing, spasmodic changes in temperature [21] and several other. An up-and-coming method is the use of high-energy radiation [22–24], which allows a controlled way to change the morphology of the defective ensemble of a specific experimental sample without changing its composition.

The most demanded for such kind of studies are HTSC compounds of the 1-2-3 $RBa_2Cu_3O_7$-d-system (where R = Y or another REM element) [25], which is caused by several reasons. First, this compound has a high critical temperature $T_c \approx 90$ K, which surpasses the boiling point of liquid nitrogen [26, 27]. Secondly, there are well-established technologies for producing cast, ceramic, film and single-crystal samples of a sufficiently large size [2]. And thirdly, the electro-physical characteristics of this compound can be quite easily varied by changing the oxygen content [28, 29], as well as the complete or partial replacement [30] of the constituent elements.

Despite a rather large number of works devoted to the study of various kinds of experimental effects on excess conductivity in the $YBa_2Cu_3O_7$-system [10], only a small part of them is devoted to the effect of irradiation on $\Delta\sigma$ [23]. In this case, as a rule, the question remains unresolved of what is the relationship between the PG and the phase transition and in which temperature region $\rho(T)$ we can talk about the end of one mechanism and the beginning of another.

In view of the foregoing, in this work, we studied the effect of irradiation by fast electrons with a dose of up to $D = 8.8{\cdot}10^{18}$ cm^{-2} on the excess conductivity of single-crystal samples of the $YBa_2Cu_3O_7$ – compound with a critical temperature near the maximum.

1. EXPERIMENT

The $YBa_2Cu_3O_{7-\delta}$ single crystals studied in this work were grown by the melt-solution method in a gold crucible [23]. All investigated crystals contained twins, the planes of which had a block structure. Resistance was measured by the standard 4-pin method. The size of the crystals was (1.5...2)×(0.2...0.3)×(0.01...0.02) mm, the smallest size corresponded to the c axis. A transport current was passed along the largest sample size; the distance between potential contacts was 1 mm. The technology of the resistive measurements, as well as the analysis of the transport properties of samples in normal and superconducting states, are described in detail in [2, 31]. Irradiation by electrons with energies of 0.5…2.5 MeV was carried out at temperatures $T < 10$ K. Note that collisions with electrons of such energies displace each of the Y, Ba, Cu, O atoms from their regular positions, and the penetration depth of such electrons are larger than the thickness of the sample [32]. Resistance was measured after each radiation dose. The doses used and the corresponding resistive parameters of the samples are presented in the Table.

2. RESULTS AND DISCUSSION

The temperature dependences of the electrical resistivity in the *ab* plane, $\rho_{ab}(T)$, and the $YBa_2Cu_3O_{7-\delta}$ crystal before and after irradiation are shown in Fig. 1. As can be seen from Fig. 1, radiation exposure leads to an abnormally strong (compared with a change in composition [29]) suppression of superconductivity (decrease in T_c) in the high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$. However, the nature of the change in the electrical and superconducting properties of HTSCs with a change in composition [2, 29] and under the action of irradiation is somewhat different. The main difference is as follows: while with a change in composition, a decrease in T_c to 86 K is usually accompanied by a change in the form of the $\rho(T)$ curves from metallic to (with c) curves, the so-called "S-shaped curve" with a characteristic thermally activated deflection [29], upon irradiation the same, in absolute value, decrease in T_c with a noticeable increase in ρ in the temperature range T_c – 300 K is not accompanied by the appearance of an S-shaped dependence $\rho(T)$. The thermally activated behaviour of electrical resistance in irradiated samples is manifested only at sufficiently low values of T_c [33]. One of the reasons leading to a sharp decrease in T_c of the irradiated samples may be the occurrence of dielectric inclusions under the action of irradiation due to the redistribution of oxygen between the O (4) and O (5) positions (in the notation of [34]) and the formation of local regions with a tetragonal structure. It can be seen that in the $\rho_{ab}(T)$ dependences in the region of relatively high temperatures, both crystals retain a fairly vast linear region, which, according to the NAFL theory [35], serves as a reliable sign of the normal state of the system. When the temperature drops below a specific characteristic value of T^*, $\rho_{ab}(T)$ deviates from a linear dependence, which indicates the appearance of some excess conductivity, which, as noted above, is due to the transition to the pseudogap mode (PG) [2, 3, 7–11]. The temperature dependence of excess conductivity is usually determined from the equation:

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

where $\sigma_0 = \rho_0^{-1} = (A+BT)^{-1}$ is the conductivity determined by extrapolating the linear section to zero temperature, and $\sigma = \rho^{-1}$ is the experimentally determined value of conductivity in the normal state. The experimental dependence $\Delta\sigma(T)$ of the initial unirradiated sample is shown in inset (*b*) to Fig. 1 in the coordinates $\ln\Delta\sigma$ – $1/T$.

It can be seen that in a sufficiently wide temperature range, this dependence has the form of a straight line, which corresponds to its description by an exponential dependence of the form:

$$\Delta\sigma \sim \exp(\Delta^*_{ab}/T), \quad (2)$$

where Δ^*_{ab} is the value that determines a certain thermal activation process through the energy gap – the "pseudogap". The value Δ^* obtained from (2) for our experimental samples is shown in the table. It can be seen that electron irradiation at maximal dose leads to a significant decrease in the absolute value of the pseudogap $\Delta^*_{before}/\Delta^*_{after} \approx 1.45$.

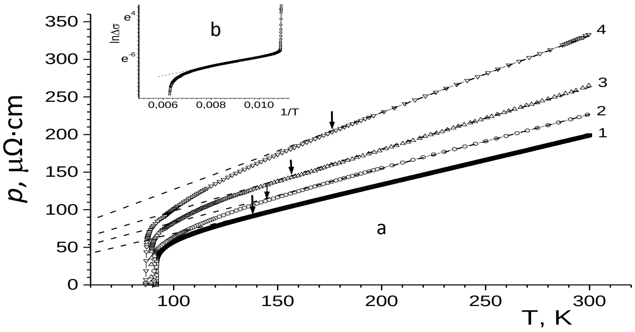

Fig. 1. Temperature dependences of the electrical resistance $\rho_{ab}(T)$ (a) and excess conductivity in the coordinates $\ln(\Delta\sigma)$ – $1/T$ (b) of the $YBa_2Cu_3O_{7-\delta}$ single crystal before and after electron training at a dose of (0; 1.4; 4.3; 8.8)·10^{18} cm^{-2} – curves 1–4, respectively. The dashed lines in Fig. (a) show the interpolation of the linear sections to the low-temperature region. The arrows indicate the temperature of transition to the pseudogap mode T. The dashed line in figure (b) shows the approximation of the experimental curve by equation (2)*

The exponential dependence $\Delta\sigma(T)$ was already observed earlier on unirradiated YBaCuO samples [36]. It was found that the approximation of experimental data can be significantly expanded by introducing a factor $(1-T/T^*)$. In this case, the excess conductivity is proportional to the density of superconducting carriers $n_s \sim (1-T/T^*)$ and inversely proportional to the number of pairs ~ $\exp(-\Delta^*/kT)$ destroyed by thermal motion:

$$\Delta\sigma \sim (1-T/T^*)\exp(\Delta^*_{ab}/T), \quad (3)$$

in this case, T^* is considered as the average mean-field temperature of the transition to the PG state, and the temperature interval $T_c < T < T^*$, in which the pseudogap state exists, is determined by the rigidity of the order parameter phase, which in turn depends on the oxygen deficiency or the concentration of the corresponding defects. Thus, using the technique proposed in [36] from the experimental curve $\ln\Delta\sigma$, it is possible to construct the temperature dependence $\Delta^*_{ab}(T)$ up to T^*. The temperature dependences of the pseudogap obtained by this technique for unirradiated and irradiated at different doses of a single crystal are shown in the given coordinates $\Delta^*(T)/\Delta_{мах} – T/T^*$ ($\Delta_{мах}$ – value of Δ^* on a plateau far from T^*, i. e. $\Delta_{мах} \approx \Delta(T << T^*) \approx \Delta(0)$) in Fig. 2 curves 1–4, respectively.

In the theoretical paper [37], the temperature dependences of the pseudogap were obtained earlier in the mean-field approximation in the framework of the BCS-BEC crossover theory for the case of weak (5) and strong (6) pairing. In general terms, these dependencies are described by the equation:

$$\Delta(T) = \Delta(0) - \Delta(0)\sqrt{\frac{\pi}{2}}\sqrt{\frac{T}{\Delta(0)}}\exp\left[-\frac{\Delta(0)}{T}\right]\times\left[1+erf\left(\sqrt{\frac{\sqrt{x_0^2+1}-1}{T/\Delta(0)}}\right)\right], \quad (4)$$

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

In the limiting case $\boldsymbol{x_0}\to\infty$ (weak pairing), the analytical expression (4) takes the form:

$$\Delta(T) = \Delta(0) - \Delta(0)\sqrt{2\pi\Delta(0)T}\,\exp\left[-\frac{\Delta(0)}{T}\right] \quad (5)$$

well known in BCS theory. At the same time, for the limit of strong interactions, in the 3-dimensional case ($\boldsymbol{x_0} < –1$), formula (4) is converted to:

$$\Delta(T) = \Delta(0) - \frac{8}{\sqrt{\pi}}\sqrt{-x_0}\left(-\frac{\Delta(0)}{T}\right)^{\frac{3}{2}}\exp\left[\frac{\sqrt{\mu^2+\Delta^2(0)}}{T}\right]. \quad (6)$$

Dependences $\Delta^*(T)/\Delta(0)$ on T/T^* calculated according to (5) and (6) for the crossover parameter $\mu/\Delta(0) = 10$ (BCS limit) and $\mu/\Delta(0) = -10$ (BEC limit) are shown in Fig. 2 by solid lines 5 and 6, respectively. Note again that $\Delta(0) \approx \Delta^*_{мах}$.

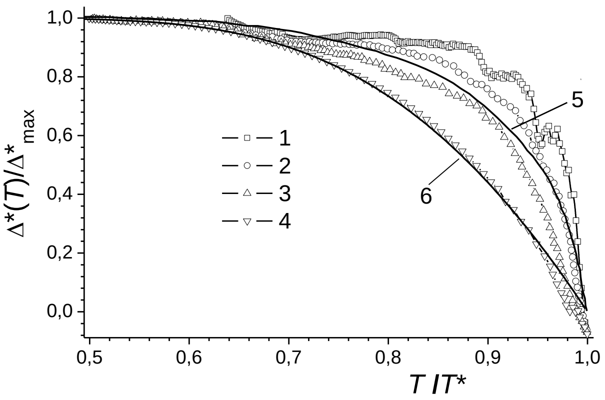

Fig. 2. Temperature dependences of the pseudogap in the given coordinates $\Delta^*(T)/\Delta^*_{мах} – T/T^*$ ($\Delta^*_{мах}$ – maximum value of Δ^* on a plateau far from T^*). The numbering of the curves corresponds to the numbering in Fig. 1.
The solid lines 5 and 6 show the dependence of $\Delta^*(T)/\Delta(0)$ on T/T^* calculated according to [37]

It is seen that in the case of a non-irradiated, optimally doped with oxygen, pure YBaCuO sample, the temperature dependence of the pseudogap experiences a significant discrepancy with theory [37], as was previously observed in the case of YBaCuO samples with a close level of deviation from oxygen stoichiometry [36]. At the same time, for a $YBa_2Cu_3O_{7-\delta}$ single crystal after irradiation, taking into account some convention for determining the magnitude of the opening of the pseudogap T^* from the deviation of the dependence $\rho(T)$ from linear behaviour, the agreement of the experiment with theory can be considered satisfactory. From Fig. 2 it can be seen that experimental curve 4 obtained after maximum exposure is well described by theoretical curve 5, corresponding to weak pairing – $\mu/\Delta(0) = 10$; experimental curves 2 and 3, obtained after irradiation at intermediate doses, are satisfactorily described by theoretical curve 5, corresponding to strong pairing – $\mu/\Delta(0) = -10$; initial curve 1 can be described, at least qualitatively, by strong pairing at $\mu/\Delta(0) = -10$. Thus, an increase in the defectiveness of the sample (without changing the composition) leads to a transition – the BCS limit, which is consistent with the results of our analysis of the applicability of the McMillan formula [37–39] – with increasing the Pr concentration in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ the electron-phonon bond decreases, tending to such values that are characteristic of BCS.

As can be seen from Fig. 1,b, as we approach T_c, there is a sharp increase in Δs. It is known that near T_c the excess conductivity is probably due to the processes of fluctuation pairing of current carriers and can be described by the power-law dependence obtained in the theoretical Lawrence-Doniakh model [6], which assumes the presence of a very smooth crossover from two-dimensional to three-dimensional fluctuation conductivity with decreasing sample temperature:

$$\Delta(T) = \left[\frac{e^2}{16\hbar d}\right]\varepsilon^{-1}\left(1 + J\varepsilon^{-1}\right)^{-\frac{1}{2}}, \qquad (7)$$

where $\varepsilon = (T - T^{mf}_c)/T^{mf}_c$ is the reduced temperature; T^{mf}_c is the critical temperature in the mean-field approximation; $J = (2\xi_c(0)/d)^2$ – interplanar pairing 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 the T_c, at $\xi_c >> d$ – the interaction between fluctuation Cooper pairs is realized in the entire volume of the superconductor – the 3D mode or far from T_c, at $\xi_c << d$ – the interaction is possible only in the planes of the conducting layers – 2D-mode) expression (2) transformed into the known relations for the three- and two-dimensional cases from the Aslamazov–Larkin theory [4]:

$$\Delta\sigma_{2D} = \left[\frac{e^2}{16\hbar d}\right]\varepsilon^{-1}, \qquad (8)$$

$$\Delta\sigma_{2D} = \left[\frac{e^2}{32\hbar \xi_c(0)}\right]\varepsilon^{-1/2}. \qquad (9)$$

In the case of comparison with experimental data, accurate determination of the value of T^{mf}_c is essential, which significantly affects the slope of the dependences $\Delta\sigma(\varepsilon)$.

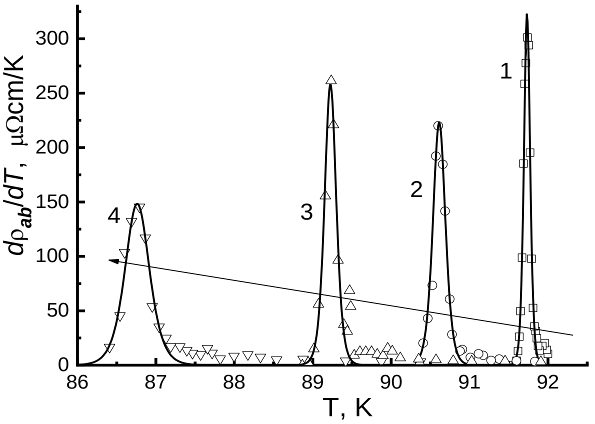

Fig. 3. Resistive transitions to the superconducting state in the $d\rho_{ab}/dT - T$ coordinates of the $YBa_2Cu_3O_{7-\delta}$ single crystal measured before and after irradiation of the sample with high-energy electrons, curves 1–4, respectively

Usually, when comparing with experimental data, $\xi_c(0)$, d, and T_c in equations (7)–(9) are adjustable parameters [1]. However, when using such a technique, as a rule, significant quantitative discrepancies between theory and experiment are observed. This, in turn, necessitates the use of the so-called *C*-factor [1] as an additional fitting parameter of the scaling factor, which allows combining the experimental data with the calculated ones and, thus, taking into account the possible inhomogeneity of the spreading of the transport current for each specific sample. In our case, T_c was taken as T^{mf}_c, which is determined, as noted above, at the maximum point on the dependences $d\rho_{ab}/dT(T)$ in the region of the superconducting transition [12], as shown in Fig. 3.

Fig. 4 shows the temperature dependences $\Delta\sigma(T)$ in the coordinates $\ln\Delta\sigma(\ln\varepsilon)$. It can be seen that in the temperature range between T_c and 1.1…1.25 T_c (depending on the oxygen content), these dependencies are satisfactorily approximated by straight lines with an inclination angle $\alpha_1 \approx -0.5$, corresponding to the exponent -1/2 in equation (8), which indicates a three-dimensional nature of fluctuation superconductivity in this temperature range. With a further increase in temperature, the decrease rate $\Delta\sigma$ significantly increases ($\alpha_2 \approx -1$), which, in turn, can be considered as an indication of a change in the dimension of the phase transition. As follows from (8) and (9), at the point of a 2D–3D crossover:

$$\varepsilon_0 = 4[\xi_c(0)/d]^2. \qquad (10)$$

In this case, having determined the value of ε_0 and using published data on the dependence of the interplanar distance on δ [31, 40], we can calculate the values of $\xi_c(0)$. As can be seen from the table, the value of $\xi_c(0)$ calculated according to (10) increases from 1.44 to 2.07 Å as *Tc* decreases, which is in qualitative agreement with the dependence of $\xi_c(0)$ on δ obtained on YBaCuO samples [29] with a gradual decrease in oxygen content. As noted above, irradiation with high-energy electrons is accompanied by a significant expansion of the region of existence of excess conductivity towards high temperatures $T > 1.5T_c$, which, cannot be explained in the framework of existing fluctuation theories [4–6, 9] and can be caused by a transition to a pseudogap the state characteristic of the "underdoped" compositions of HTSC compounds [2, 7, 8]. On the other hand, it cannot be excluded that this feature can also be partially due to the presence of an additive contribution to the conductivity from impurity phases with higher T_c. For example, even in the studies of the phase transition in HTSC compounds [40], it was shown that although superconducting phases with $T_c > 140$ K are structurally unstable under normal conditions, they can exist as impurity phases in doped and multiphase samples.

Thus, electron irradiation leads to a significant expansion of the region of existence of excess conductivity, while the coherence length increases by more than 1.4 times.

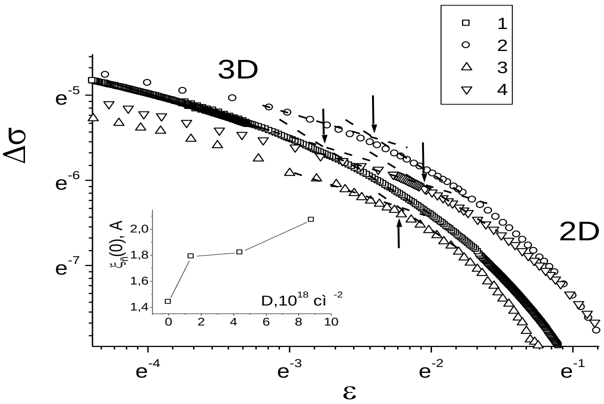

Fig. 4. Dependences $\Delta\sigma(T)$ in the coordinates $\ln\Delta\sigma(\ln\varepsilon)$. The numbering of the curves corresponds to the numbering in Fig. 1. The inset shows the dependences $\xi_c(0)$ on the radiation dose D

If we determine the transition temperature from the PG to the FP mode, T_f, from the point of deviation of the value of lnΔs up from the linear dependence of lnΔσ(1/T) [36], we can estimate the relative length of the existence of the PS mode as $t^*=(T^*-T_f)/T_f$. The calculation results show that after irradiation to the maximum dose, the total relative expansion of the temperature domain of the PG is more than doubled, from t^* = 0.4345 to 0.9488. One of the possible reasons for this unusual behaviour of the lnΔσ(1/T) dependences of the irradiated $YBa_2Cu_3O_{7-\delta}$ samples during irradiation can be specific mechanisms of quasiparticle scattering [41–43] and relaxation of the defective ensemble, which we discussed in more detail in [44–46].

Dose x 10^{18} 1/cm^2	T_c, K	ρ_{ab}(300), μΩ·cm	T^*, K	Δ^*_{ab}, MeV	T_f, K	$t^*=(T^*-T_f)/T_f$	α_1	α_2	ε_0	$\xi_c(0)$, Å
0	91.7	199	137	97.1	95.5	0.4345	-0.501	-1.044	0.064	1.44
1.4	90.60	227	143	81.7	94.3	0.5164	-0.499	-1.032	0.094	1.79
4.3	89.24	267	156	103.5	90.8	0.7181	-0.503	-1.009	0.097	1.82
8.8	86.8	332	175	66.9	89.8	0.9488	-0.491	-1.015	0.125	2.07

α_1, α_2 – angular ratios in the coordinates lnΔσ(lnε) (see Fig. 4); ε_0 – crossover reduced temperature – equations (7) and (10).

CONCLUSIONS

In conclusion, we briefly summarize the main results obtained in this paper. In this work, the evolution of the excess conductivity of $YBa_2Cu_3O_{7-\delta}$ single crystals upon the phased irradiation with high-energy electrons is investigated. The excess conductivity, Δσ(T), of $YBa_2Cu_3O_{7-\delta}$ single crystals before and after electron irradiation in a wide temperature range $T_f < T < T^*$ is subject to exponential temperature dependence. Moreover, the description of excess conductivity using the relation $\Delta\sigma \sim (1-T/T^*)\exp(\Delta^*_{ab}/T)$ can be interpreted in terms of the mean-field theory, where T^* presented as the mean-field temperature of the superconducting transition and the temperature dependence pseudogaps are satisfactorily described in the framework of the BCS–BEC crossover theory. An increase in the defectiveness of the sample (here, due to irradiation with electrons) leads to the BEC crossover (strong pairing) → BCS (weak pairing). Irradiation of the $YBa_2Cu_3O_{7-\delta}$ single crystal by electrons leads to the effect of expanding the temperature interval for the realization of the PS mode, thereby narrowing the region of the linear dependence $\rho(T)$ in the *ab*-plane. The dependence of the coherence length in the direction of the c axis, $\xi_c(0)$, on the radiation dose is obtained. It was shown that an increase in the radiation dose from 1.4 to $8.8\cdot10^{18}$ cm^{-2} leads to a significant expansion of the temperature range for the existence of excess conductivity. In this case, the value of $\xi_c(0)$ increases by more than 1.4 times and the 2D–3D crossover point shifts in temperature.

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ЭВОЛЮЦИЯ ИЗБЫТОЧНОЙ ПРОВОДИМОСТИ МОНОКРИСТАЛЛОВ $YBa_2Cu_3O_{7-\delta}$ ПРИ ВОЗДЕЙСТВИИ ОБЛУЧЕНИЯ ВЫСОКОЭНЕРГЕТИЧЕСКИМИ ЭЛЕКТРОНАМИ

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Исследована эволюция избыточной проводимости монокристаллов $YBa_2Cu_3O_{7-\delta}$ при облучении электронами. Показано, что облучение электронами приводит к значительному расширению температурного интервала существования избыточной проводимости, тем самым, сужая область линейной зависимости $\rho(T)$ в ***ab***-плоскости. Установлено, что избыточная проводимость $\Delta\sigma(T)$ монокристаллов $YBa_2Cu_3O_{7-\delta}$ в широком интервале температур $T_f<T<T^*$ 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 перехода в ПЩ-состояние, а температурная зависимость псевдощели удовлетворительно описывается в рамках теории кроссовера БКШ-БЭК. При этом величина поперечной длины когерентности $\xi c(0)$ увеличивается в 1,4, раза и смещается по температуре точка 2*D*-3*D* кроссовера.

ЕВОЛЮЦІЯ НАДЛИШКОВОЇ ПРОВІДНОСТІ МОНОКРИСТАЛІВ $YBa_2Cu_3O_{7-\delta}$ ПРИ ВПЛИВІ ОПРОМІНЕННЯ ВИСОКОЕНЕРГЕТИЧНИМИ ЕЛЕКТРОНАМИ

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Досліджено еволюцію надлишкової провідності монокристалів $YBa_2Cu_3O_{7-\delta}$ при опроміненні електронами. Показано, що опромінення електронами призводить до значного розширення температурного інтервалу існування надлишкової провідності, тим самим, звужуючи область лінійної залежності $\rho(T)$ в ***ab***-площині. Встановлено, що надлишкова провідність $\Delta\sigma(T)$ монокристалів $YBa_2Cu_3O_{7-\delta}$ в широкому інтервалі температур $T_f<T<T^*$ 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 середньополева температура переходу в ПЩ-стан, а температурна залежність псевдощілини задовільно описується в рамках теорії кросовера БКШ-БЕК. При цьому величина поперечної довжини когерентності $\xi c(0)$ збільшується в 1,4 рази, і зміщується по температурі точка 2*D*-3*D* кросовера.