ANALYSIS OF FLUCTUATION CONDUCTIVITY IN $Y_{0,5}Cd_{0,5}Ba_2Cu_3O_{7-\delta}$

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The mechanism of the formation of excess conductivity in cuprate HTSCs $YBa_2Cu_3O_{7-\delta}$ and $Y_{0,5}Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ was considered in the framework of the model of local pairs, taking into account the Aslamazov - Larkin theory near T_c^{mf} . The temperature Tcr of the transition from the 2D fluctuation region to the 3D region (the temperature of the 2D-3D crossover) is determined. The values of the coherence length of fluctuation Cooper pairs ξ_c (0) along the c axis are calculated. It is shown that partial substitution of Y for Cd in the Y-Ba-Cu-O system leads to an increase in $\xi_c(0)$ by ~ 3.2 times (from 1.1 Å to 3.6 Å), as well as to an expansion as a region of existence pseudogap, and the region of superconducting (SC) fluctuations near T_c^{mf}. The temperature dependence of the pseudogap $\Delta^*(T)$ and the values of Δ^* (T_c^{mf}) were determined, and the temperatures T_m (122.7K) corresponding to the maximum of the temperature dependence of the pseudogap in $Y_{0,5}Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ were estimated. The maximum values of the pseudogap in the $Y_{0,5}Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ sample are 660K.

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INTRODUCTION

The anomalous properties of layered metal oxide high-temperature superconductors (HTSC) are one of the most important problems in modern solid-state physics [1]. In experiments on the charge transfer dynamics in such systems, a number of objective difficulties arise, including the rather complex crystal structure of HTSCs [2, 3], the nonuniform distribution of structural defects [4], the presence of intergrain boundaries and cluster inclusions [5], and the inhomogeneity of specific experimental samples [6], which is often caused by different technological prehistories, etc.

The physical properties of HTSCs are also unusual, especially in the normal state, where a pseudogap (PG) opens along the excitation spectrum at the characteristic temperature $T^* >> T_c$ [7, 8] (T_c is the critical temperature of the superconducting (SC) transition).

It is believed that the correct understanding PG physics, which remains one of the most intriguing properties of cuprates [9], will shed light on the SC pairing mechanism in HTSCs.

Since the discovery of HTSCs with active plane CuO_2 (cuprates), attempts have been made to improve their superconducting characteristics by isomorphic substitutions of one of the components [11, 12].

One of the most interesting materials for studying the properties of HTSCs is the $YBa_2Cu_3O_{7-\delta}$ (YBCO) compound, because it is possible to widely vary its composition by replacing yttrium with its isoelectronic analogues, or by changing the degree of oxygen non-stoichiometry. In YBCO, yttrium is replaced by a majority of lanthanides and other elements [1, 12-14], which usually does not lead to the deterioration of the compound's superconducting properties. Pr is an exception, since PrBCO is an insulator [15].

It is wellknown that ions of rare earth elements and K replace yttrium atoms. Accordingly, Sr is incorporated into the positions of Ba atoms, while other dopants are incorporated into the Cu(1) position [16]. However, this process is not well understood. The mechanisms of how a modification impacts the properties of HTSCs in underdoped and overdoped regimes remain unclear, which is important since fulfilling the conditions of these regimes is necessary to achieving the optimal properties of HTSC materials. The effect of substitution on fluctuation processes and the PG is, likewise, poorly understood. Therefore, the study of substitution in the classical structure of $YBa_2Cu_3O_{7-\delta}$ provides new data on the mechanism of superconductivity and the contribution made to superconductivity by Y, Ba, and Cu atoms.

HTSC materials are synthesized with partial substitution of Cd for Y in YBa2Cu3O*x*, because despite the fact that yttrium and cadmium are heterovalent, their ionic radii are similar (0.90 and 0.95 Å, respectively). This serves as the basis for such a substitution in YBaCuO.

The goal of this study is to investigate how possible defects and structural changes impact the physical parameters, fluctuation characteristics, and PG after substituting Cd $YBa_2Cu_3O_{7-\delta}$. A sample (Y1) $YBa_2Cu_3O_{7-\delta}$ and (Y2) $Y_{0,5}Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ were studied. In this case, the resistivity ρ (T) of the Y2 sample in the normal phase at 300 K in comparison with Y1 increases by almost 13 times.

The fluctuation conductivity (FLC) is analyzed within the framework of the Aslamazov–Larkin (AL) and Hikami–Larkin (CL) theories [17, 18]. Near *Tc*, the FLC of all samples, $\triangle\sigma(T)$, is perfectly described by the threedimensional (3D) equation of the AL theory, which is typical for HTSCs [1, 15]. To analyze the temperature dependence of the pseudogap, the model of local pairs proposed in [19] was used.

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EXPERIMENTAL RESULTS AND THEIR PROCESSING

The $Y_{0,5}Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ samples are prepared in two stages [12]. At the first step, the initial components, which are in a stoichiometric ratio, are mixed and annealed in air at a temperature of 1120 K for 25 h. At the second step, the resulting compositions are annealed in oxygen (P = 1.2–1.5 atm) at a temperature of 1190 K for 25 h, and slowly cooled to room temperature. In this work, we analyze the results of replacing Y with Cd at x = 0.5.

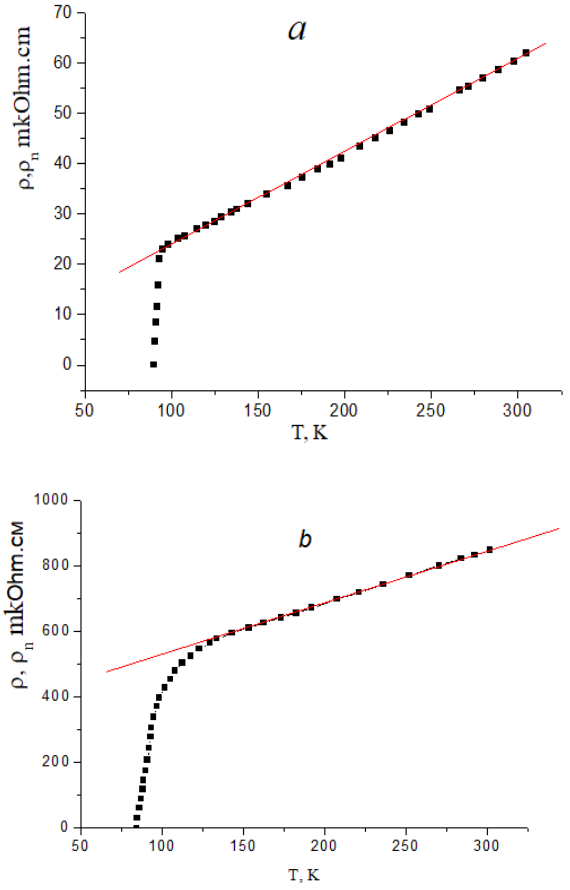

Fig. 1. Temperature dependences of the resistivity of the samples $YBa_2Cu_3O_{7-\delta}$ (a) and $Y_{0,5}Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ (b). Straight lines denote ρ_n (T) extrapolated to low temperatures.

Samples 8×4×3 mm in size are cut from compressed tablets (12 mm diameter and 3 mm thickness) of synthesized polycrystalline material. The electrical resistance is measured according to the standard four-probe method. The current contacts are created by applying a silver paste and subsequently connecting silver conductors with 0.05 mm diameters to the ends of the polycrystalline sample, in order to ensure the current spreads across it in a uniform manner. The potential contacts located at the middle of the sample's surface are created in a similar way. Then, a three-hour annealing process is carried out at a temperature of 200 °C in an oxygen atmosphere. This procedure makes it possible to obtain a contact transition resistance of 1 Ω and to perform resistive measurements at transport currents of up to 10 mA in the *ab*-plane.

The temperature dependences of the resistivity ρ (T) = ρab (T) of the synthesized polycrystals Y1 and Y2 are shown in Fig. 1. The ρ(T) dependences at different values of have a shape characteristic of optimally doped HTSCs [20]. One exception is the nonlinear dependence ρ(T) at Y1, $\rho(T) \sim T^2$, which is typical for overdoped cuprates [20]. Analysis shows that the data in this case are well approximated by the equation $\rho(T) = \rho_0 + B_1(T) + B_2 (T)^2$ with the parameters ρ_0 = 9.07, B_1 = 0.1442, and B_2 = 0.0000957, obtained by approximating data using the Origin computer program. The coefficient of the quadratic term is very small, but nonzero. Thus, we have an overdoped sample. This result is particularly interesting, since it is impossible to obtain an overdoped sample of $YBa_2Cu_3O_{7-\delta}$ simply by oxygen intercalation. The maximum that can be obtained is δ = 0 and an oxygen index 7– δ = 7, at $T_c \sim 92$ K [20]. It is most likely that such a dependence ρ(T) is specific to this polycrystalline sample.

As seen in Fig. 1, the critical temperatures of the samples of the Y – Ba – Cu – O system upon doping with Cd in the considered case remain up to ~ 85 K. In this case, the resistivity ρ (T) of the Y2 samples in the normal phase at 300 K in comparison with $YBa_2Cu_3O_{7-\delta}$ increases by almost 13 times.

To determine the temperature of the beginning of the formation of local pairs [3,4] in the samples (T *), the criterion [ρ (T) –ρ_0] / aT = 1 was used, which reflects the transformation of the equation of a straight line [39], where ρ0 is the residual resistance cut off by this line on the Y axis at T=0. In this case, it is defined as the temperature of deviation of ρ (T) from 1.

FLUCTUATION CONDUCTIVITY

The linear course of the temperature dependence of the specific resistance of samples Y1 and Y2 in the normal phase is well extrapolated by the expressions $\rho_n(T) = (D+ \kappa T +BT^2)$ and $\rho_n(T) = (\rho_0+ \kappa T +BT^2)$ (here D, B and k are some constants). This linear relationship, extrapolated to the low temperature range, was used to determine excess conductivity Δσ(T according to:

$$\Delta\sigma(T) = \rho^{-1}(T) - \rho_v^{-1}(T). \qquad (1)$$

The analysis of the behavior of excess conductivities was carried out in the framework of the local pair model [4].

Assuming the possibility of the formation of local pairs [(3), 4] in the Y2 sample at temperatures below T * = 136.6 K, the experimental results obtained near Tcmf were analyzed taking into account the occurrence of fluctuation Cooper pairs (PCPs) above Tc within the framework of the Aslamazov - Larkin theory (AL) [17] (fiq.2).

The Fig. 2 shows dependence of the logarithm of the excess conductivity of the samples Y1 (1) and Y2 (2) on the logarithm of the reduced temperature $\varepsilon = (T / T_c^{mf}-1)$. According to the theory of AL, as

well as Hikami – Larkin (HL) developed for HTSC [18], in the region of $T>T_c$ (but near T_c^{mf}), the fluctuation coupling of charge carriers occurs, leading to the appearance of fluctuation conductivity (FC). In this region, the temperature dependence of excess conductivity on temperature is described by the expressions:

$$\Delta\sigma_{AJI3D} = C_{3D}\{e^2/[32\hbar\xi_c(0)]\}\varepsilon^{-1/2}, \quad (2)$$

$$\Delta\sigma_{AJI2D} = C_{2D}\{e^2/[16\hbar d]\}\varepsilon^{-1}, \quad (3)$$

respectively for three-dimensional (3D) and two-dimensional (2D) region. The scaling coefficients C are used to combine the theory with experiment [4].

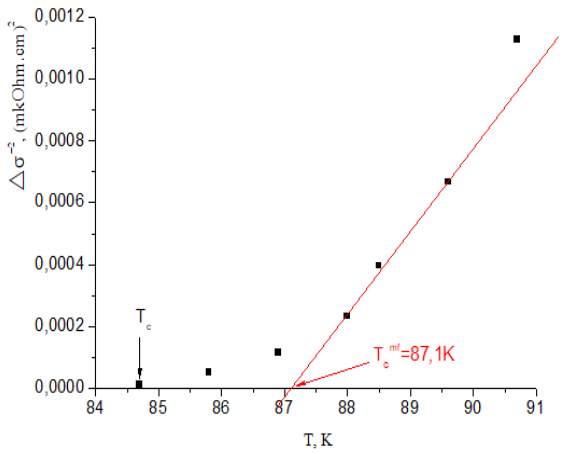

Fig.2. Temperature dependence of the inverse square of the excess conductivity $\Delta\sigma^{-2}$ (T) of the $Y_{0,5}Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ polycrystal.

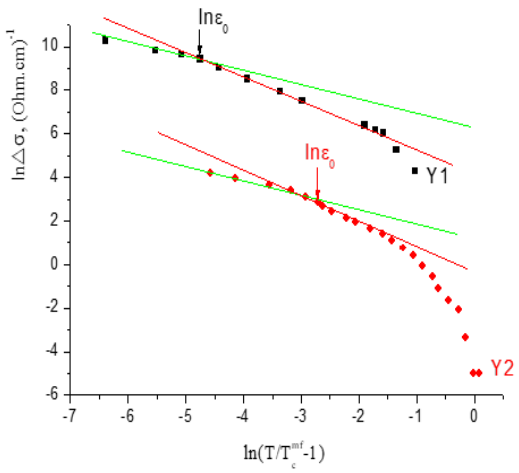

Fig. 3. Dependences of the excess conductivity logarithm on ln (T / T_c^{mf} -1) for samples Y1 and Y2. Solid lines - calculation within the framework of the Aslamazov-Larkin theory.

Thus, by the angle of inclination α of dependences ln (Δσ) as a function of ε = ln (T / T_c^{mf}-1) (see Fig. 3), we can distinguish 2D (tgα = -1) and 3D (tgα = - 1/2) regions of phase transition. It can also determine the crossover temperature T_0 (the transition temperature from $\Delta\sigma_{2D}$ to σ_{3D}) and the tangents of the slopes of the dependences Δσ(T) corresponding to the exponents ε in equations (2) and (3). The corresponding values of the parameters 2D and 3D regions determined from the experiment for sample Y1 are 2D (tgα = -1.04) and 3D (tgα = -0.5) and for Y2 2D (tgα = -1) and 3D (tgα = -0.5).

On basis of value the temperature of the crossover T_0, which corresponds to $\ln\varepsilon_0$, according to Fig. 3, it can determine the coherence length of local pairs along the c axis [18,19]:

$$\xi_c(0) = d\sqrt{\varepsilon_0}\,, \quad (4)$$

here d ≈ 11.7Å is the distance between the inner conducting planes in Y-Ba-Cu-O [20]. The values of ξ_c (0) = 1.1 Å ($\ln\varepsilon_0 \approx -1.2318$) for Y1 and ξ_c (0) = 3.6 ($\ln\varepsilon_0 \approx -2.347$) for Y2 was obtained, accordingly.

ANALYSIS OF THE MAGNITUDE AND TEMPERATURE DEPENDENCE OF THE PSEUDOGAP

As noted above, in the cuprates at T<T *, the density of electron states of quasiparticles on the Fermi level decreases [21] (the cause of this phenomenon is not yet fully elucidated), which creates conditions for the formation of a pseudogap in the excitation spectrum and it leads ultimately to the formation of an excess conductivity. The magnitude and temperature dependence of the pseudogap in the investigated samples was analyzed using the local pair model, taking into account the transition from Bose-Einstein condensation (SCB) to the BCS mode predicted by the theory [18] for HTSC when the temperature decreases in the interval T * <T <T_c. Note that excess conductivity exists precisely in this temperature range, where fermions supposedly form pairs - the so-called strongly coupled bosons (PRS). The pseudogap is characterized by a certain value of the binding energy $\varepsilon_b \sim 1/\xi^2(T)$, causing the creation of such pairs [18], which decreases with temperature, because the coherence length of the Cooper pairs $\xi(T)=\xi(0)(T/T_c-1)^{-1/2}$, on the contrary, increases with decreasing temperatures. Therefore, according to the LP_model, the SCB are transformed into the FCP when the temperature approaches T_c (BEC-BCS transition), which becomes possible due to the extremely small coherence length ξ (T) in cuprates.

From our studies, we can estimate the magnitude and temperature dependence of PG, based on the temperature dependence of excess conductivity in the entire temperature range from T * to T_c^{mf} according to [21]:

$$\Delta\sigma(\varepsilon) = \left\{\frac{A(1-T/T^*)[\exp(-\Delta^*/T)]e^2}{16\hbar\xi_c(0)\sqrt{2\varepsilon_0^* \cdot sh(2\varepsilon/\varepsilon^*_0)}}\right\} \quad (5)$$

where the (1-T / T *) determines the number of pairs formed at T ≤ T *: and the exp (-Δ */T) determines the

number of pairs destroyed by thermal fluctuations below the BEC-BCS transition temperature. The coefficient A has the same meaning as the coefficients C_{3D} and C_{2D} in (2) and (3).

The solution of equation (5) gives the value of Δ *:

$$\Delta^*(T) = T \cdot \ln\left\{ \frac{A(1-T/T^*)e^2}{\Delta\sigma(T)16\hbar\xi_c(0)\sqrt{2\varepsilon_0^* \cdot sh(2\varepsilon/\varepsilon^*_0)}} \right\} \quad (6)$$

where Δσ (T) is the experimentally determined excess conductivity.

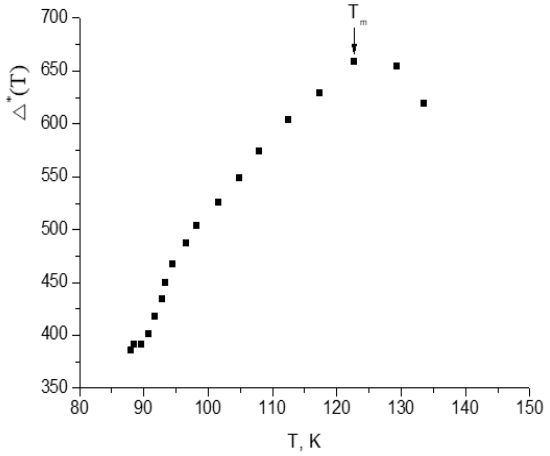

Fig.4. Temperature dependences of the calculated pseudogap for the sample Y2. The arrows show the maximum values of the pseudogap value.

The temperature dependence and the value of the pseudogap parameter Δ * (T) (Fig. 4) were calculated based on equation (6). with the parameters given above. Note that no PG is observed in Y1, since the sample is in overdoped mode. As noted in [21], the value of the coefficient A is selected from the condition of coincidence of the temperature dependence of Δσ equation (5), assuming Δ* = Δ*(T)). with experimental data in the region of 3D fluctuations near T_c. According to [21, 22], the optimal approximation for the HTSC material is achieved with values of $2\Delta^*(T)/K_BT) \approx 5 \div 7$. For sample Y2, the $2\Delta^*(T_c)/K_BT_c = 5$. As a result, from the LP analysis for Y2, the values A=6.95 and $\Delta(T_c^{mf})$ = 87,1·2,5=217,7K, were obtained, which is consistent with the experimental data.

The temperature dependences of Δ*(T) obtained on the basis of equation (6) are in Fig. four. The maximum values of the pseudogap for Y2 $\Delta^*(T_m) \approx$ 660 K, T_m = 122,7K have been determined.

From the presented data in Fig. 4, it is also seen that as T decreases, the pseudogap value first increases, then, after passing through a maximum, decreases.

This decrease is due to the transformation of the SCB in the PCF as a result of the BEC-BCS transition, which accompanied by an increase in excess conductivity at $T \rightarrow T_c$. Such a behavior of Δ * with decreasing temperature was first found on YBCO films [21,22] with different oxygen contents, which seems to be typical of cuprate HTSC [21]. Thus, we can come to the conclusion that in the $Y_{0,5}Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ investigated by us, the formation of local pairs of charge carriers at $T >> T_c^{mf}$ is possible, which creates conditions for the formation of a pseudogap [21,22] with the subsequent establishment of the phase coherence of fluctuation Cooper vapor at $T < T_c^{mf}$.

CONCLUSION

The investigation of the effect of partial substitution of Y bu Cd on the mechanism of excess conductivity in Y-Ba-Cu-O polycrystals showed that partial substitution of Y by Cd leads to a decrease in the critical temperatures of the $Y_{0,5}$ $Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ (Y2) sample compared to $YBa_2Cu_3O_{7-\delta}$ (Y1) (respectively T_c^{mf}(Y2)=87,1K и T_c^{mf}(Y1)=91,99K T_c). In this case, the resistivity of the $Y_{0,5}$ $Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ sample in the normal phase at 300 K increases (13 times) as compared to $YBa_2Cu_3O_{7-\delta}$, and the increase in the coherence length of Cooper pairs is 3.27 times (1.1 and 3.6 Å, respectively).

Studies and analysis have shown that the excess conductivity Δσ (T) in $Y_{0,5}$ $Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ in the temperature range $T_c^{mf} < T < T^*$ is satisfactorily described in the framework of the model of local pairs.

The result of the analysis of the pseudogap state by the excess conductivity method confirmed that the model of local pairs in this case is applicable for the $Y_{0,5}$ $Cd_{0,5}Ba_2Cu_3O_{7-\delta}$ image.

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