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2*D*–3*D* CROSSOVER OF THE IN-PLANE PARACONDUCTIVITY IN OPTIMAL DOPED $ReBa_2Cu_3O_{7-\delta}$ (Re = Y, Ho) SINGLE CRYSTALS

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The effect of the fluctuation paraconductivity in optimal oxygen-doped $ReBa_2Cu_3O_{7-\delta}$ (Re = Y, Ho) single crystals has been investigated. The results indicate that the theoretical model of Aslamazov–Larkin (AL) describes the temperature dependence of fluctuation paraconductivity (FP) near the critical temperature (T_c). At temperatures above the temperature of the 2D–3D crossover this dependence is appropriately described by the Lawrence–Doniach (LD) theory. The extended linear dependence of $\rho_{ab}(T)$, in the crystal with the minimum critical temperature indicates that we have a high defect concentration in this sample. This in turn causes negative processes into forming fluctuation pairs.

Introduction

In high-temperature superconductors the dimensionality of critical fluctuations near the superconducting instability is important for understanding the mechanism responsible for the superconductivity. It has been established that the small value of the coherence length and the quasi-layer structure causes the development of a wide fluctuation area in the temperature dependence of the high critical temperature T_c superconducting cuprates (HTSC) [1–5]. The variation of the oxygen stoichiometry [4] and impurities [3] has a significant role in the behaviour of HTSC as this influences significantly the processes of forming fluctuation Cooper pairs. This in turn affects the realization of different regimes for the existence of fluctuation conductivity (FC) at temperatures above T_c [2]. The conductivity characteristics of the HTSC compounds can be tailored through total or partial substitu-

tion of their components. In this aspect, the $YBa_2Cu_3O_{7-\delta}$ compound has been studied more thoroughly and the majority of rare-earth elements, when substituted for yttrium, yielded superconductors. This is a consequence of the relatively easy way in substituting yttrium with its iso-electron rare-earth analogues. In spite of the significant number of experimental studies, the issue of the dimensionality of the superconducting subsystem in temperatures nearby T_c, still remains undetermined. This is due to the fact that the experimental work was mostly carried out on ceramics, films and textured samples, with different methodologies (see for example [1,3–5]).

Single crystals are advantageous compared to polycrystalline samples as the influence of grain boundaries on electrical characteristics is eliminated and anisotropic properties can be measured directly. The principal aim of this work is to investigate the evolution of the FC properties of YBaCuO single crystals in which yttrium has been substituted directly with holmium.

Experimental techniques

The $ReBa_2Cu_3O_{7-\delta}$ (Re = Y, Ho) single crystals were grown in a gold crucible in the temperature range of 850–970°C by means of the self-flux method as it was described in detail in a previous study [2]. To obtain samples with an optimal oxygen content ($\delta < 0.1$), the crystals were annealed in an oxygen flow at a temperature of 400°C for five days. For the resistivity measurements the produced single crystals had dimensions 2 × 0.3 × 0.02 mm (K1 sample, YBaCuO), 2 × 0.8 × 0.07 mm (K2 sample, HoBaCuO) and 1.8 × 0.9 × 0.06 mm (K3 sample, HoBaCuO) with the **c**-axis oriented along the smallest dimension. Silver electrocontacts were connected to the surface of the crystals by means of silver paste. The electrical resistance was measured using the standard four-contact method for two opposite 1 mA direct current directions in zero magnetic field. The temperature was measured by a copper-constantan thermocouple.

Results and discussion

The temperature dependence of the in-plane (*ab*-plane) resistivity of the three single crystals studied is represented in Fig. 1. It is evident that in all cases the dependence has a quasi-metal behavior characterized from the existence of a long linear section at high temperatures.

At the same time the small value of the in-plane resistivity at room temperature, ρ_{ab}(300 K) (156, 135 and 125 μΩ·cm for the K1, K2 and K3 crystals respectively), in conjunction with the high critical temperature ($T_c \approx 91$ K) and the narrow width of the superconducting transition ($\Delta T_c \leq 0.3$ K for K1 and $\Delta T_c \approx 0.5$ K for K2 and K3**)** proves the high quality of the samples.

The ratio ρ_{ab}(300 K)/ρ_{ab}(0 K) is 40, 12.5 and 12 for the K1, K2 and K3 crystals respectively, where the ρ_{ab}(0 K) refers to the point where the extrapolated linear section of the in-plane resistivity $\rho_{ab}(T)$ is crossing the ρ-axis of Fig. 1,*a*,*b*.

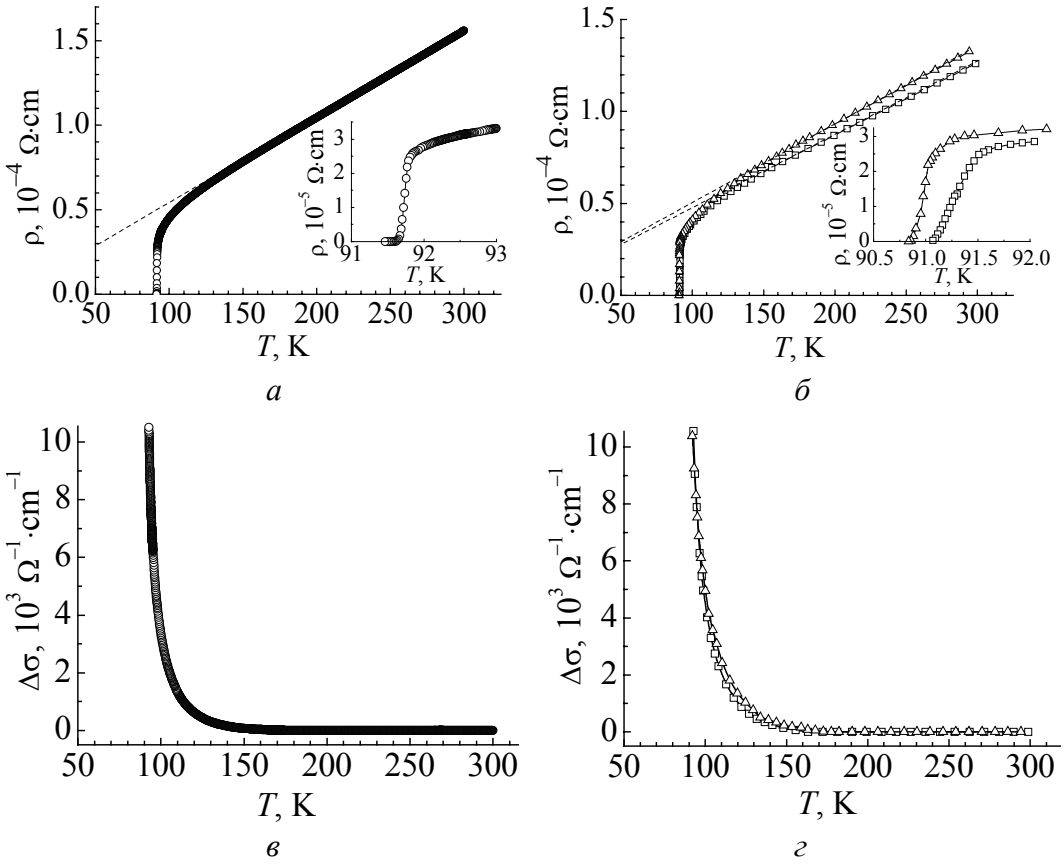

Fig. 1. Temperature dependence of in-plane resistivity $\rho_{ab}(T)$ for K1 (*a*) K2 and K3 (*b*) single crystals and of additional conductivity $\Delta\sigma(T)$ (*c*, *d*): ○ – K1, □ – K2, Δ – K3. Insets of Fig. 1,*a*,*b*: resistivity transition into superconducting condition of the three samples. The shape of symbols of the curves in the insets is in accordance to that of symbols in the figure

It is evident from Fig. 1 that for temperatures $T < 160$ K there appears a deviation from the linear dependence. This is due to an additional conductivity, the temperature dependence of which is described using the following relation:

$$\Delta\sigma(T) = \sigma(T) - \sigma_0(T) = \frac{\rho_0(T) - \rho(T)}{\rho_0(T)\rho(T)}, \qquad (1)$$

where $\sigma = \rho^{-1}$ is the experimental value of the conductivity and $\sigma_0 = \rho_0^{-1} = (A + BT)^{-1}$ is the conductivity defined by extrapolation of the linear section to 0 K. The temperature dependence of additional conductivity is shown in Fig. 1,*c* for crystal K1 and in Fig. 1,*d* for crystals K2 and K3.

The most likely cause for the origination of this additional paraconductivity near T_c is the fluctuational pairing of the carriers. The theory of fluctuation conductivity in anisotropic structures is described by the AL model [6]. This model was further refined in the work of LD [7] and the fluctuational correction in conductivity can be described with an equation of the form:

$$\Delta\sigma = \frac{e^2}{16d\hbar\varepsilon}\left\{1+\left[\frac{2\xi_c(0)}{d}\right]^2\varepsilon^{-1}\right\}^{-1/2}. \qquad (2)$$

Here ξ_c is the coherence length along the **c**-axis, $\varepsilon = (T - T_c^{mf})/T_c^{mf}$ is the reduced temperature, T_c^{mf} is the critical temperature and d is the two-dimensional thickness of the layer.

Near T_c ($\xi_c >> d$) the interaction between the fluctuation Cooper pairs is realized for the three-dimentional regime of the superconductor. Consequently, Eq. (2) takes the form:

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

Away from T_c ($\xi_c << d$) the interaction is possible only in the two-dimensional regime in the surface of the conducting layers. Eq. (2) is then transformed to:

$$\Delta\sigma_{2D} = \frac{e^2}{16\hbar d}\varepsilon^{-1}. \qquad (4)$$

T_c^{mf} is significant for the calculation of $\Delta\sigma(T)$. In this study T_c^{mf} is the point where the extrapolated linear section of $\Delta\sigma^{-2}(T)$ is crossing the temperature axis, as shown in the inset (*a*) of Fig. 2 and has been previously demonstrated through the work of B. Oh *et al*. [1].

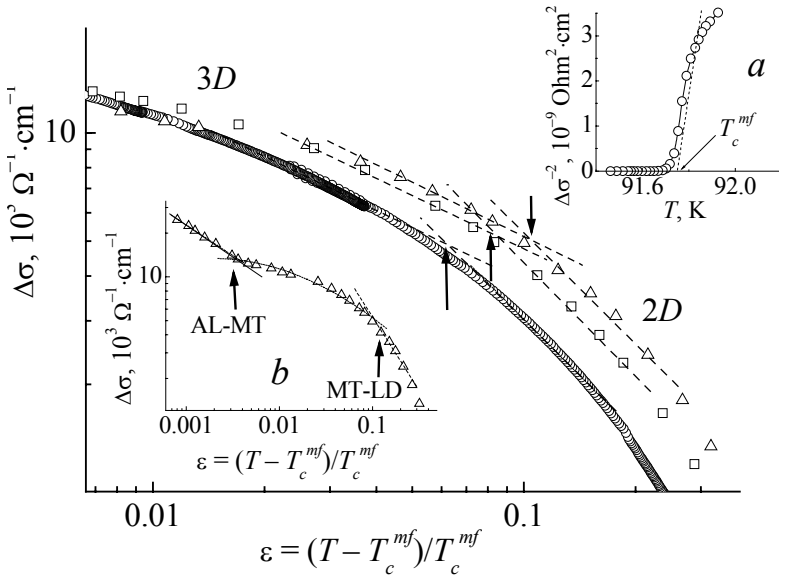

Fig. 2. Plot of lg$\Delta\sigma$ versus the logarithm of the reduced temperature $\varepsilon = (T - T_c^{mf})/T_c^{mf}$ for K1, K2 and K3 single crystals. Inset (*a*) presents the technique for calculating T_c^{mf} for the $\Delta\sigma^{-2}(T)$ dependence (K1 sample). Inset (*b*) shows double AL–MT–LD crossover for the lg$\Delta\sigma$(lgε) dependence (K3 sample). The crossover point is indicated in the figure by arrows. The shape of symbols of the curves is consistent to Fig. 1.

The relationship between $\Delta\sigma$ and the reduced temperature ε in coordinates $\lg\Delta\sigma$–$\lg\varepsilon$ is shown in Fig. 2. In this figure the 2*D*–3*D* crossover can be determined as the transition from the 3*D* regime ($\alpha_1 = d\ln\Delta\sigma/d\ln\varepsilon \approx -0.5$) to the 2*D* regime ($\alpha_2 = d\ln\Delta\sigma/d\ln\varepsilon \approx -1.0$). Applying Eqs. (3) and (4), at the 2*D*–3*D* crossover point:

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

In this case the value of the coherence length $\xi_c(0)$ can be calculated with Eq. (5) by inseting the values of crossover temperature ε_0 and d (as lattice constant $c \approx 11.7$ Å [8]). The values $\xi_c(0)$, have been calculated, with using this method, to be 1.5 ± 0.3; 1.7 ± 0.3 and 1.9 ± 0.3 Å for $T_{c1}^{mf} = 91.73$; $T_{c2}^{mf} = 91.3$ and $T_{c3}^{mf} = 90.95$ K for the K1, K2 and K3 crystals, respectively. These results are comparable to $\xi_c = 2.3 \pm 0.5$ Å, that was determined from the measurement of the magnetic permeability [2] for pure YBaCuO single crystals. Furthermore, from inset (*b*) of Fig. 2 it can be observed that the K3 crystal, which has the lowest critical temperature, demonstrates the strongest displacement of the 2*D*–3*D* crossover. This indicates the existence of the intermediate FC-regime in sample K3, which was proved in the theoretical Maki–Thompson (MT) model [9]. The MT model assumes the domination of the processes of scattering of fluctuating Cooper pairs by normal carriers. Double AL–MT–LD crossover has been observed in a previous study [4] for the case of an YBaCuO film with a minor variation in stoichiometry. It should be also noted that in Fig. 1,*b* the $\rho_{ab}(T)$ dependence of the K3 crystal is characterized by an extended linear section, which is the longest among the investigated samples and indicates the existence of a higher degree of defects in the structure of the sample. The increase in the concentration of defects can narrow the margins of the FP existence and displace the 2*D*–3*D* crossover point [5].

Conclusion

The substitution of Y with Ho in the $YBa_2Cu_3O_{7-\delta}$ single crystals does not change essentially the critical temperature and the conductivity parameters. The $\Delta\sigma(T)$ dependence of the additional paraconductivity around T_c is well described by the theoretical AL model and the equation of the LD theory for the 2*D*–3*D* crossover point transition for the samples considered. Sample K3 (that has a lower T_c than the other samples) has a strong displacement of the 2*D*–3*D* crossover, which leads to the existence of a double AL–MT–LD crossover. The lower T_c of sample K3 combined with the increased width of the $\rho_{ab}(T)$ linear dependence section, indicates a higher concentration of defects in the sample. This has a consequence to the prevention of the processes of forming fluctuation pairs and displacement of the 2*D*–3*D* crossover point by the temperature.

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