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In-plane paraconductivity of $ReBa_2Cu_3O_{7-\delta}$ (Re=Y, Ho) single crystals with a given topology of planar defects and a mono-domain sample

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In this experimental study we present a comparative analysis between the normal and the fluctuating conductivity of the $ReBa_2Cu_3O_{7-\delta}$ (Re=Y, Ho) single crystals (with a given topology of plane defects) and a mono-domain sample (without twin boundaries). It is demonstrated that the twin boundaries are efficient scattering centers for the normal and fluctuating carriers. The Lawrence-Doniach theoretical model is an appropriate description of the temperature dependence of the excess conductivity. The values of the coherence length perpendicular to the ab-plane $x_c(0)$ are in good agreement with the values derived from magnetic measurements of stoichiometric $YBa_2Cu_3O_{7-\delta}$ single crystals.

Keywords: fluctuation conductivity, $YBa_2Cu_3O_{7-\delta}$ single crystals, twin boundaries, crossover, coherence length.

У роботі проведено порівняльний аналіз нормальної і флуктуаційної провідності монокристалів $ReBa_2Cu_3O_{7-\delta}$ (Re=Y, Ho) із заданою топологією площинних дефектів та бездвійникового однодоменного зразка. Показано, що двійникові межі є ефективними центрами розсіювання нормальних і флуктуаційних носіїв. При цьому значення довжини когерентності перпендикулярно базисній площині $x_c(0)$, отримані при апроксимації температурної залежності надлишкової провідності теоретичною моделлю Лоуренса-Доніаха,. задовільно узгоджуються із значеннями отриманими з магнітних досліджень для оптимально допованих киснем монокристалів $YBa_2Cu_3O_{7-\delta}$

Ключові слова: флуктуаційна провідність, монокристали $YBa_2Cu_3O_{7-\delta}$, межі двійників, кросовер, довжина когерентності.

В работе проведен сравнительный анализ нормальной и флуктуационной проводимости монокристаллов $ReBa_2Cu_3O_{7-\delta}$ (Re=Y, Ho) с заданной топологией плоских дефектов и бездвойникового мононодоменного образца. Показано, что двойниковые границы являются эффективными центрами рассеивания нормальных и флуктуационных носителей. При этом значения длины когерентности перпендикулярно базисной плоскости $x_c(0)$, полученные при аппроксимации температурной зависимости избыточной проводимости теоретической моделью Лоуренса-Дониаха,. удовлетворительно согласуются со значениями, полученными из магнитных исследований для оптимально допированных кислородом монокристаллов $YBa_2Cu_3O_{7-\delta}$.

Ключевые слова: флуктуационная проводимость, монокристаллы $YBa_2Cu_3O_{7-\delta}$, границы двойников, кроссовер, длина когерентности.

Introduction

Various different fluctuating pairing modes of carriers have been studied extensively since the early studies of high-temperature superconductors [1-4]. The composition and the topology of the defect assembly that defines the flow conditions of the transport current and the carrier transport scattering mechanisms are significant. Compounds from the system $ReBa_2Cu_3O_{7-\delta}$ (Re=Y or rare earth ion), are technologically important and their study is motivated from previous work on single crystals production technology. It should also be noted that in this system it is easy to substitute yttrium (Y) with most rare earth ions.

In the past, most experimental work has been focused on ceramics, films and textured samples, with different methodologies. As a result, numerous aspects of the realization of different fluctuating pairing modes of carriers have remained unclear until now. It must also be appreciated that in $YBa_2Cu_3O_{7-\delta}$ single crystals, there exist plane defects such as twin boundaries [4,5] that affect the transport current properties in the normal and the fluctuating conductivities. This effect has not been investigated thoroughly due to the experimental difficulties in determining the contribution of twin boundaries. The aim of the present study is to investigate the evolution of the fluctuating conductivity regime in single crystals containing a controllable defect structure but differing in the transport current geometry. For comparison a mono-domain sample, in which the plane defects where removed by using special procedures was considered.

Experimental techniques

The single crystals of $ReBa_2Cu_3O_{7-\delta}$ (Re=Y, Ho) were grown using the solution-melt technique in a gold crucible described in a previous study [4]. In previous experiments [4,5], it was demonstrated that when the $YBa_2Cu_3O_{7-\delta}$ compounds were saturated with oxygen, the structure transforms from tetragonal to orthorhombic. This structural change is associated with the crystal twinning to minimize the elastic energy. Figure 1 is a photograph of the characteristic twin grid of the $YBa_2Cu_3O_{7-\delta}$ single crystal (sample K1).

For the resistivity measurements thin single crystals were selected with permeable twin boundaries. In these single crystals the area with uniform direction of twin boundaries had dimensions of 0.5×0.5 mm^2. This geometry enabled to cut out bridges with parallel twin boundaries with a width of 0.2 mm. The area with uniform direction of twin boundaries bridges had a contact spacing of 0.3 mm (see insets of Figure 2).

Bridges B2 and B3 were cut from the same batch of the crystal (K1 sample, $YBa_2Cu_3O_{7-\delta}$) and bridges B4 (K2 sample, $HoBa_2Cu_3O_{7-\delta}$) and B5 (K3 sample, $HoBa_2Cu_3O_{7-\delta}$) were grown from the same batch and had practically identical resistivity parameters. The experimental geometry was selected so that the transport current vector, **I**, was either parallel, **I**||TB (B2 bridge, K1 sample, $YBa_2Cu_3O_{7-\delta}$ and B4 bridge, K2 sample, $HoBa_2Cu_3O_{7-\delta}$), perpendicular, **I**⊥TB (B3 bridge, K1 sample, $YBa_2Cu_3O_{7-\delta}$), or under an angle of $\alpha=45^\circ$ (B5 bridge, K3 sample, $HoBa_2Cu_3O_{7-\delta}$) to

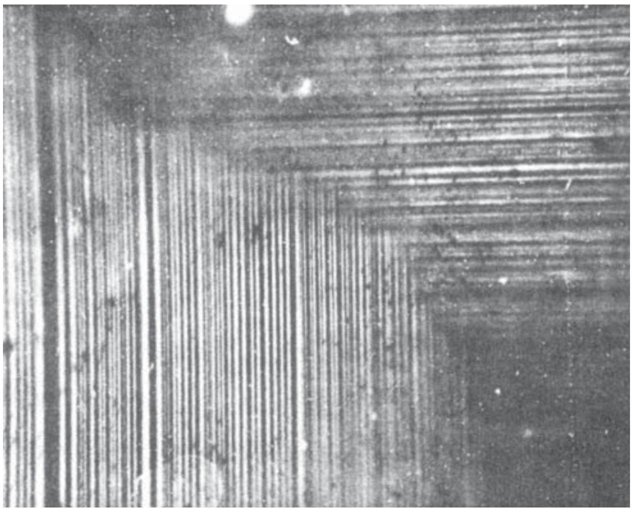

Fig. 1. Photograph (polarized light x 550) of the $YBa_2Cu_3O_{7-\delta}$ (sample K1) single crystal where its characteristic twin grid is visible.

the twin boundaries. A part of the K1 single crystal was cut to acquire a sample without twin boundaries (bridge B1), with dimensions of 1x0.3x0.2 mm^3 (the *c* axis oriented along the smallest dimension). After the selection, the sample was untwinned in a special cellule with a temperature of 720 K and a pressure range of 30-40 GPa, according to the method described in a previous study [5]. In order to have stoichiometric oxygen concentration, the crystal was annealed in an oxygen atmosphere flow for three days. The high quality of the experimental samples and the stoichiometry in the oxygen content is proved by the narrow superconducting transition width (ΔT_c<0.5K), the high critical temperature ($T_c\approx$92K) and the low electrical resistivity ($\rho\approx$120-150 $\mu\Omega$.cm). The derived experimental parameters are given in Table 1.

The electric contacts were formed according to the

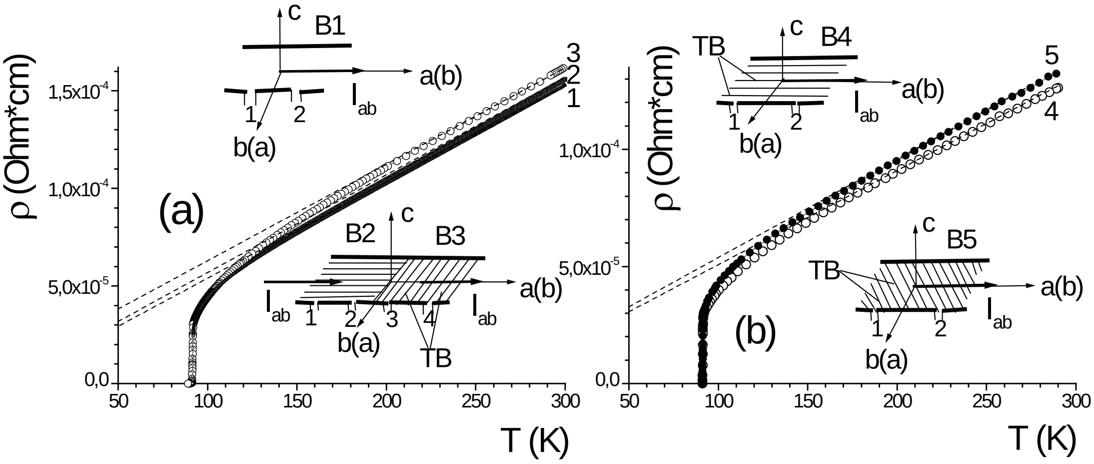

Fig. 2. Temperature dependence of the in-plane resistivity $\rho_{ab}(T)$ for bridges (a) B1, B2, B3 and (b) B4, B5 . The schematic representation of the experimental geometry is shown in the corresponding insets.

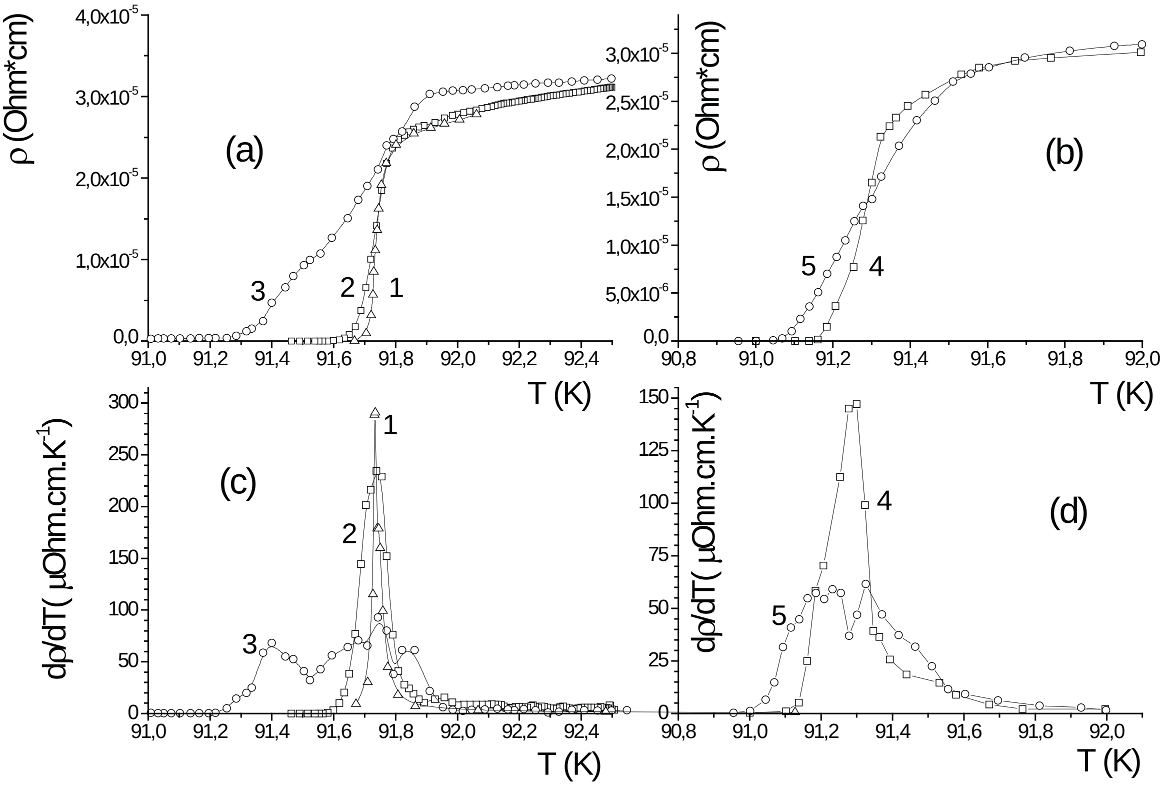

Fig. 3. Resistivity transition into the superconducting condition in (a), (b) ρ_{ab} – T coordinates and in (c), (d) $d\rho_{ab}/dT$ – T coordinates, for bridges (a), (c) B1, B2, B3 and (b), (d) B4, B5 (curves 1 – 5, respectively).

standard four-contact scheme by applying silver paste onto the crystal surface and the connection of silver conductors (0.05 mm in diameter) followed by 3 hours annealing at 200 °C in an oxygen atmosphere. This procedure provided a contact transition resistance of less than 1 Ω and made it possible to measure the resistivity at transport currents up to 10 mA in the ab-plane, in the temperature drift mode, for two opposite directions of the transport current. The temperature was measured with a copper-constantan thermocouple; the voltage was measured across the sample and the reference resistor with V2-38 nano-voltmeters.

Results and discussion

Figure 2 shows the temperature dependence of the electric resistivity in the *ab*-plane, $\rho_{ab}(T)$, for the five analyzed samples. Figure 3 illustrates the resistive superconducting transitions in ρ_{ab} - T [Figure 3 (a) and (b)] and in $d\rho_{ab}/dT$ – T [Figure 3 (c) and (d)] coordinates. According to previous studies [2,3], the maximum point, corresponding to the inflection point, in the $d\rho_{ab}(T)/dT$ dependence, is the critical temperature of the resistive superconducting transition. The narrow superconducting transition width (ΔT_c<0.5 K) shows the high quality of the samples. It can be determined (from Figure 3 and Table 1) that the untwined sample has the lowest superconducting transition width (ΔT_c≈0.2 K). The samples with **I**||TB geometry (bridges B2 and B4) have ΔT_c≈0.3-0.4 K, when the twin boundaries impact to the carrier scattering processes is minimized. An additional lower peak (maximum point) in the curve, corresponding to **I**⊥TB [bridge B3, Figure 3(c)] and α=45° [bridge B5, Figure 3(d)] can be due to the effect of twin boundaries provided that the ordering parameter is somewhat suppressed [6].

It can be seen from Figure 2 that the $\rho_{ab}(T)$ dependence has a metallic character for all the samples considered. For the $YBa_2Cu_3O_{7-\delta}$ crystals the resistivity for the untwinned sample and for the sample with the **I**||TB orientation, at room temperature, is about 5-7% lower than that for **I**⊥TB. For $HoBa_2Cu_3O_{7-\delta}$ crystals the resistivity of the sample with the **I**||TB orientation is lower than the α=45° sample. As the vector **I** is oriented relative to crystallographic axes in the same way for all the cases considered the greater ρ_{ab} value at **I**⊥TB and α=45° is explained by the current carrier scattering at the twin boundaries. The electron free path in the single crystals has been estimated to be 0.1 μm [7]. The value of the electron free path is one order smaller than the twin spacing. The maximum resistance

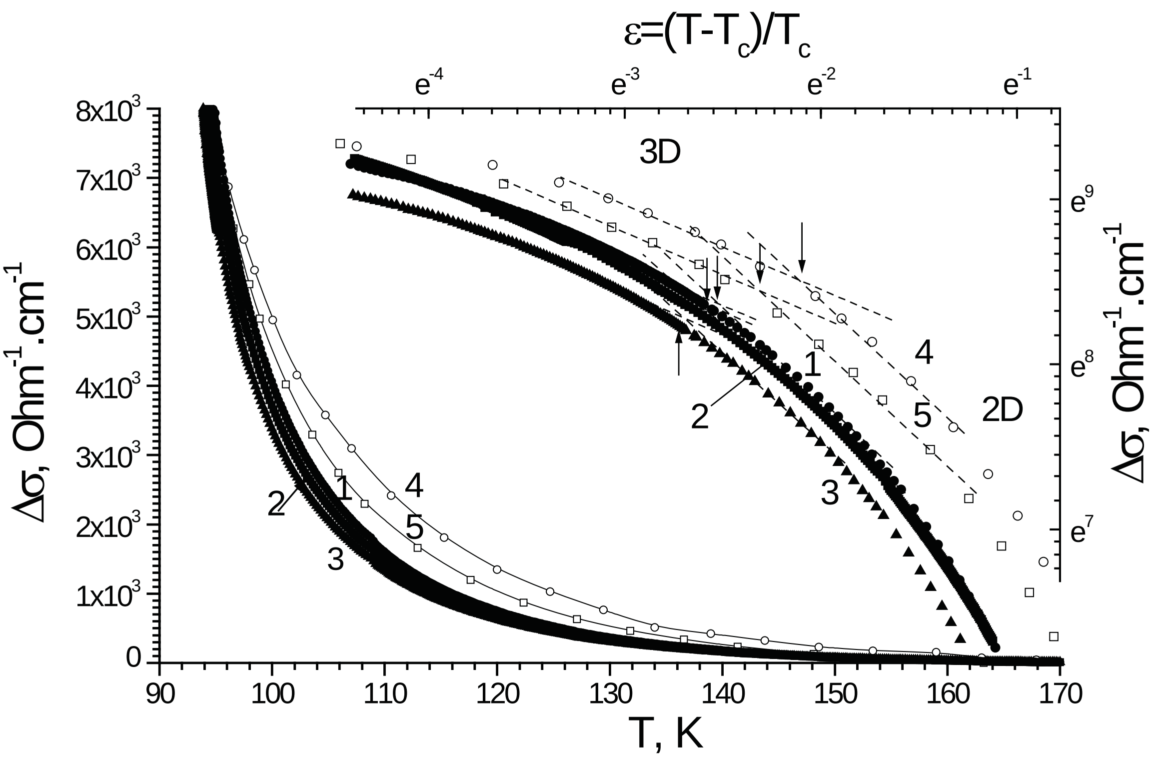

Fig. 4. The temperature dependence of the excess conductivity Δσ(T) for bridges B1-B5 (curves 1 – 5, respectively) in lnΔσ - lnε coordinates, respectively. The numbering of the curves is consistent to Figures 2 and 3. Arrows indicate the 2D-3D crossover points.

increase due to scattering at the twin boundaries is 10%. The observed 5 -7% increase in ρ_{ab} is due to the efficient carrier scattering at the twin boundaries.

Above 150 K, the temperature dependence of the resistivity is approximately linear (see Figure 2). Below 150 K, the resistivity deviates from linearity and there exists an excess conductivity determined by:

$$\Delta\sigma = \sigma - \sigma_0 \qquad (1)$$

where σ_0 is the conductivity value determined by extrapolating the linear section of $\sigma = (A+BT)^{-1}$ to zero temperature and σ is the experimental conductivity in the normal state. The electron subsystem dimensionality in layered superconductors is defined by the relationship between the coherence length along the c axis (ξ_c) and the 2D layer thickness (d). For the case when $d < \xi_c$, the interaction between the fluctuating pairs occurs within the whole superconductor volume (3D mode). On the other hand, when $d > \xi_c$, the interaction is possible only in superconductive layers (2D mode). Two basic theoretical models have been proposed to describe the fluctuation conductivity mode in layered superconductors [8,9]. In the Lawrence and Doniach model [9], the temperature dependence of the fluctuation conductivity is described by:

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

where $\varepsilon=(T-T_c)/T_c$ and e is the electron charge.

Near T_c, at $\xi_c >> d$ (3D mode), this equation is transformed into [7]:

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

Far from T_c, at $\xi_c << d$ (2D mode), into:

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

It is important for the analysis of the experimental data to have a precise determination of the T_c.

In Figure 4 the temperature dependence of the excess conductivity (in Δσ - T and lnΔσ - lnε coordinates) is given. In this figure, T_c is defined as the critical temperature value T_c^{mf} in the approximation of mean field theory at the point:

$$\left(\frac{\partial^2\rho}{\partial T^2}\right)_{T=T_c^{mf}} = 0 \qquad (5)$$

This corresponds to the maximum in the $d\rho_{ab}/dT$ dependence in the superconductive transition [2,3]. In Figure 4, near T_c, the $\Delta\sigma(T)$ dependence is approximated well by equation (3) (power index -0.5), thus evidencing the 3D character of fluctuating superconductivity within this temperature range. As the temperature increases further, the slope of $ln\Delta\sigma(ln\,\varepsilon)$ relationship increases significantly. This can be considered as an indication of the fluctuation conductivity dimensionality change. Equations (3) and (4) are equal in the 2D-3D-crossover point and therefore the following relation must be satisfied:

$$\xi_c(0)\varepsilon^{-1/2} = d/2 \quad (6)$$

Having determined the ε_0 value in the 2D-3D crossover point and taking d = 11.7 Å for $ReBa_2Cu_3O_{7-\delta}$ (Re=Y, Ho) [10], it is possible to determine the $\xi_c(0)$ value. These results as well as the characteristic slope values of the $\ln\Delta\sigma(\ln\varepsilon)$ function are presented in Table 1. It should be stressed that this methodology does not allow the consideration of possible errors in the resistivity measurements when determining the fluctuation values within spatially inhomogeneous systems, which are associated with the presence of small inclusions of other phases, even in high quality single crystals [6]. Consequently, when comparing with the experimental data, the $\xi_c(0)$, d and T_c values in equations (2) – (4), are considered to be fitting parameters. An additional scaling multiplier, the C-factor, to assist in the calculation of the inhomogeneity of the current transport distribution in each specific sample is required [1]. Using this methodology equation (2) has the best agreement with the experimental data. The coherence length $\xi_c(0)$ is 2±0.3 Å for the $ReBa_2Cu_3O_{7-\delta}$ compound, when the orientation is **I**⊥TB and 2.2±0.3 Å for the untwined sample, as well as in the case of **I**||TB orientation. Comparing the data obtained from the experiment and the magnetic susceptibility data measured in a previous study [11], the diamagnetic contribution of the area with high T_c, is proportional to the volume of this phase. The ξ_c value obtained was ξ_c=2.3±0.5 Å, closer to the values calculated using the second method. Nevertheless, the difference between the $\xi_c(0)$ values calculated with both methodologies for the **I**⊥TB, α=45° and **I**||TB bridges and for the untwined sample are consistent. Specifically, they are 10% to 14%, and provide evidence of the influence of twin boundaries on the formation processes of the fluctuating Cooper pairs.

Conclusions

The resistance increase within the linear section of ρ(T) between the transport current perpendicular I⊥TB, $\alpha=45^0$, as compared to the case of I||TB and the untwined sample, is due to an efficient scattering of normal carriers at the twin boundaries. The excess conductivity functions, Δσ(T), are described by the Lawrence-Doniach theoretical model. Twin boundaries in the crystal intensify the de-pairing processes of the fluctuating carriers and swift the 2D-3D crossover point.

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Table 1.

Material properties as determined at different bridges.

Bridge	T_c, K	ΔT_c, K	ρ_{ab}(300), μΩ.cm	ε_0	tanα $_{3D}$	tanα $_{2D}$	$\xi_c(0)$, Å
B1 (without TB)	91.734	0.2	153	0.070	-0.501	-1.008	1.55
B2 (**I**||TB)	91.738	0.3	156	0.065	-0.498	-1.017	1.49
B3 (**I**⊥TB)	91.743	0.5	163	0.057	-0.512	-1.044	1.40
B4 (**I**||TB)	91.301	0.4	129	0.103	-0.489	-0.998	1.88
B5 ($\alpha=45^0$)	91.325	0.5	138	0.092	-0.505	-1.015	1.77