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Effect of twin boundaries on scattering processes of normal and fluctuating carriers in $YBa_2Cu_3O_{7-\delta}$ single crystals

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Effect of twin boundaries on the normal and fluctuating conductivity of YBaCuO single crystals has been studied. The temperature dependence of the excess conductivity has been shown to be described satisfactorily by the Lawrence-Doniach theoretical model. The twin boundaries are efficient scattering centers of normal and fluctuating carriers. The determined values of coherence length perpendicular to the *ab* plane $\xi_c(0)$ agree satisfactorily with those obtained from magnetic measurements for stoichiometric YBaCuO crystals.

Исследовано влияние границ двойникования на нормальную и флуктуационную проводимость монокристаллов YBaCuO. Показано, что температурная зависимость избыточной проводимости удовлетворительно описывается теоретической моделью Лоуренса-Дониаха. Двойниковые границы являются эффективными центрами рассеяния нормальных и флуктуационных носителей. Полученные значения длины когерентности перпендикулярно *ab*-плоскости $\xi_c(0)$, удовлетворительно согласуются со значениями, полученными из магнитных исследований для монокристаллов YBaCuO стехиометрического состава.

The realization of various fluctuating pairing modes of carriers is studied intensely starting from the earliest investigation stages of high-temperature superconductors (HTSC) [1–3]. Of great importance therein is the composition and topology of the defect ensemble that defines the running conditions of the transport current and the carrier scattering mechanisms. As most experimental works was carried out on ceramics, films and textured samples, differing in technologic pre-history, numerous aspects of the problem remain unclear up to now. Taking into consideration the above, this work is aimed at study of the evolution of the fluctuating conductivity (FC) mechanism is single crystals containing a controllable defect structure and differing in the transport current geometry.

The HTSC single crystals of $YBa_2Cu_3O_{7-\delta}$ compounds were grown using the solution-melt technique in a gold crucible as has been described in detail in [4]. For the resistive studies, rectangular crystals of $3\times0.5\times0.03$ mm^3 size were selected. It is known [4], that as YBaCuO compounds are saturated with oxygen, the tertra-ortho structure transition takes place which, in its turn, causes the crystal twinning, thus minimizing its elastic energy. To obtain the samples containing the singly-directed twin boundaries (TB), a 0.2 mm wide bridge with the contact spacing of 0.3 mm was cut out of the sample as is shown in the inset (a) to Fig. 1.

The experimental geometry was selected so that the transport current vector **I** was either parallel or perpendicular to the twin planes. The electric contacts were formed according to the standard four-contact scheme by applying silver paste onto the crystal surface followed by connection of silver conductors of 0.05 mm in dia. and

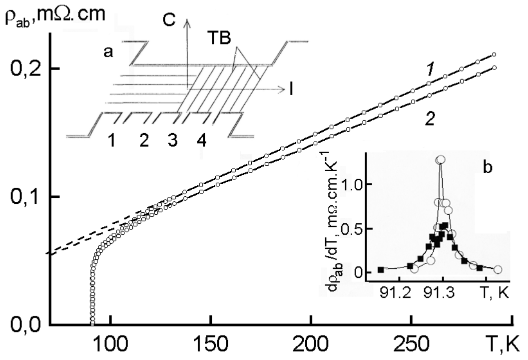

Fig. 1. Temperature dependences of electric resistivity $\rho_{ab}(T)$ for I⊥TB and I||TB orientations (curves *1* and *2*, respectively). Inset (a): scheme of bridge used in resistive studies. Inset (b): resistive transitions to the superconductive state in $d\rho_{ab}/dT-T$ coordinates for I⊥TB and I||TB orientations (dark and light symbols, respectively).

3 h aneealing at 200°C in oxygen atmosphere. This procedure provided the contact transition resistance less than 1 and made it possible to carry out the resistive measurements at the transport currents up to 10 mA in the *ab* plane. The measurements were carried out in the temperature drift mode. The temperature was measured with a copper-constantan thermocouple, the voltage across the sample and across the reference resistor, with V2-38 nanovoltmeters. The voltmeter signals were transferred to a PC through an interface.

Fig. 1 presents the temperature dependences of electric conductivity in the *ab* plane $\rho_{ab}(T)$ for two bridge parts, the inset (b) illustrating the resistive superconducting transitions thereof in $d\rho/dT-T$ coordinates. According to the procedure [3], the maximum position corresponding to the inflection point in those dependences is considered as the critical temperature of the resistive superconducting transition. The narrow superconducting transition width ($\Delta T_c < 0.3$ K) evidences the high quality of the samples. At the same time, a low additional peak in the curve corresponding to I⊥TB experimental geometry is possibly due to the effect of TBs where the ordering parameter may be somewhat suppressed [5].

It is seen in Fig. 1 that the $\rho_{ab}(T)$ are of metallic character in both cases. At **I**⊥TB orientation, the conductivity at room temperature is about 5 % lower than that for **I**⊥TB. As the vector **I** is oriented relatively to crystallographic axes in the same manner in both bridge parts, the larger *ab* value at **I**⊥TB can be explained by the current carrier scattering at TBs. The electron free path in the single crystals has been estimated as 0.1 μm [6], being one order smaller than the twin spacing. Therefore, the maximum resistance increase due to scattering at TBs may attain 10 %. Thus, the obtained 5 % ρ_{ab} increase evidences the efficient carrier scattering at TB.

It follows from Fig. 1 that above 150 K, the temperature dependence of resistance is approximately linear. Under that temperature, the resistivity is deviated downward from linearity, that results in appearance of a certain excess conductivity determined as a rule from the equality

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

where σ_0 is the conductivity value determined by extrapolating the linear section of $\sigma = (A + B{\cdot}T)^{-1}$ relationship to zero temperature and σ is the experimental conductivity in the normal state. According to the existing concepts, the electron subsystem dimensionality in layered superconductors is defined by relationship between ξ_c (coherence length along **c** axis) and d (the 2D layer thickness). When $d < \xi_c$, the interaction between the fluctuation pairs is realized within the whole superconductor volume (3D mode) while at $d > \xi_c$, the interaction is possible only immediately in superconductive layers (2D mode). The basic theoretical models to describe the FC mode in layered superconductors have been proposed by Aslamazov and Larkin [7] as well as by Lawrence and Doniach [8]. According to [8], the temperature dependence of FC is described by equation

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

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

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

while far from T_c, at $\xi_c < d$ (2D mode), into

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

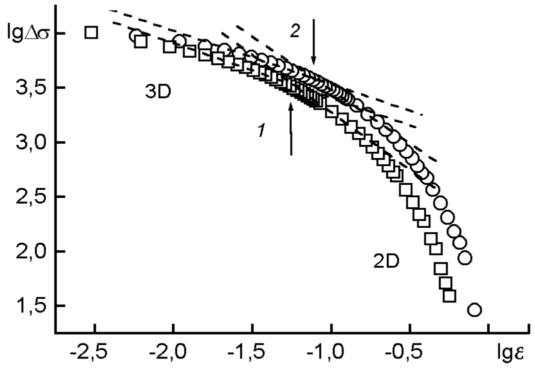

Fig. 2. lgΔσ(lgε) dependences for I⊥TB and I||TB orientations (curves *1* and *2*, respectively). The 2D-3D crossover points are shown by arrows.

where $\varepsilon = (T - T_c)/T_c$. The precise T_c determination is of great importance when processing the experimental data.

Fig. 2 presents the temperature dependences of excess conductivity in $\lg\Delta\sigma - \lg\varepsilon$ coordinates. The T_c is there defined as the critical temperature value T_c^{fm} in the approximation of mean field theory determined in the point

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

corresponding to the maximum in the $d\rho/dT$ dependence in the superconductive transition area [3]. It is seen in Fig. 2 that near T_c, the $\Delta\sigma(T)$ dependence is approximated well by Eq.(3) at the power index −0.5, thus evidencing the 3D character of fluctuating superconductivity within this temperature range. As the temperature rises further, the slope of lgΔσ(lgε) relationship increases appreciably. This, in turn, can be considered as an indication on the FC dimensionality change. It follows from (3) and (4), in the 2D-3D crossover point, the equality

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

should be met. Then, having determined the ε_0 value in the 2D-3D crossover point and taking $d = 11.7$ Å for $YBa_2Cu_3O_{7-\delta}$ [4], it is possible to determine $\xi_c(0)$. The calculation results obtained using the formula (6) as well as characteristic slope values of the lgΔσ(lgε) function corresponding to power indices in (3) and (4) for two bridge parts are presented in the Table.

Table

Bridge	T_c^{mf}, K	ε_0	α_{3D}	α_{2D}	$\xi_c(0)$, Å
I‖TB	91.31	0.058	−0.515	−1.031	1.41
I⊥TB	91.30	0.076	−0.501	−0.977	1.61

It is to note, however, that the use of that calculation procedure does not allow to take into account the possible error of the resistive measurements when determining the fluctuating quantities is spatially inhomogeneous systems associated with the small inclusions of another phase even in the high-quality single crystals [5]. Thus, when comparing with experimental data, $\xi_c(0)$, d, and T_c in Eqs.(2)–(4) are considered usually to be fitting parameters. A scaling factor, so-called *C*-factor, is also introduced that makes it possible to take into account the transport current distribution inhomogeneity in each specific sample [1].

Using the procedure, the best coincidence with experimental data has been obtained for Eq.(2). In this case, the coherence length $\xi_c(0)$ amounted 2±0.3 Å and 2.2±0.3 Å for I⊥TB and I‖TB orientations, respectively. In this aspect, of interest is to compare the obtained results with the magnetic susceptibility data measured in [9] where determined was the diamagnetic contribution from the area with high T_c being in proportion to the volume content of that phase. The ξ_c value obtained from those experiments is 2.3±0.5 Å, being closer to the values calculated using the second method.

Nevertheless, when using both the first and second calculation methods, the difference between the $\xi_c(0)$ values for I⊥TB and I‖TB experimental geometries amounts 10 to 14 %, thus evidencing an effective influence of TB on the formation processes of fluctuating Cooper pairs.

Thus, the resistance increase within the linear section of $\rho(T)$ dependences at the transport current orientation I⊥TB as compared to the case of I‖TB evidences an efficient scattering of normal carriers at the TB. The excess conductivity functions $\Delta\sigma(T)$ are described satisfactorily by the Lawrence-Doniach theoretical model. The presence of TBs in the crystals may favor the intensification of de-pairing processes of fluctuating carriers, thus extending the linear $\rho(T)$ area in the *ab* plane and shifting the 2D-3D crossover point.

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Вплив двійникових меж на процеси розсіювання нормальних і флуктуаційних носіїв у монокристалах $YBa_2Cu_3O_{7-\delta}$

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Досліджено вплив меж двійників на нормальну і флуктуаційну провідність монокристалів YBaCuO. Показано, що температурна залежність надлишкової провідності задовільно описується теоретичною моделлю Лоуренса-Доніаха. Двійникові границі є ефективними центрами розсіювання нормальних і флуктуаційних носіїв. Одержані значення довжини когерентності перпендикулярно *ab*-площині $\xi_c(0)$, задовільно узгоджуються із значеннями, одержаними з магнітних досліджень для монокристалів YBaCuO стехіометричного складу.