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Scattering Processes of Normal and Fluctuating Carriers in $ReBa_2Cu_3O_{7-\delta}$ (Re = Y, Ho) Single Crystals with Unidirectional Twin Boundaries

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The effect of twin boundaries on the normal and fluctuating conductivity of ReBaCuO (Re = Y, Ho) single crystals was investigated. The results indicate that the Lawrence–Doniach theoretical model describes adequately the temperature dependence of the excess conductivity. The twin boundaries are efficient scattering centers for normal and fluctuating carriers. The derived values of the coherence length perpendicular to the *ab*-plane $\xi_c(0)$ are in good agreement with those obtained from magnetic measurements for stoichiometric YBaCuO crystals.

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1. Introduction

The occurrence of various fluctuating pairing modes of carriers has been studied thoroughly since the earliest investigation stages of high-temperature superconductors (HTSC) [1–3]. An important consideration is the composition and topology of the defect assembly that defines the flow conditions of the transport current and the carrier transport scattering mechanisms. It therefore follows that the materials with most potential to study are the compounds from the system $ReBa_2Cu_3O_{7-\delta}$ (Re = Y or other rare earth ion). It must be appreciated that in YBaCuO single crystals, there exist plane defects such as twin boundaries (TB) [4], which in turn affect the transport current properties in the normal and the fluctuating conductivities. This effect has not been investigated thoroughly due to the difficulty in determining the contribution of TB. The aim of this work is to study the evolution of the fluctuating conductivity (FC) mechanism in single crystals containing a controllable defect structure and differing in the transport current geometry.

2. Experimental techniques

The HTSC single crystals of $ReBa_2Cu_3O_{7-\delta}$ (Re = Y, Ho) compounds were grown using the solution-melt technique in a gold crucible described in a previous study [4]. For the resistivity measurements the rectangular single crystals selected had dimensions $3.0 \times 0.5 \times 0.04$ mm^3 (K1 sample, bridges B1, B2, YBaCuO), $2 \times 0.8 \times 0.07$ mm^3 (K2 sample, bridge B3, HoBaCuO) and $1.8 \times 0.9 \times 0.06$ mm^3 (K3 sample, bridge B4, HoBaCuO) with the c axis oriented along the smallest dimension. Samples K2 and K3 (both HoBaCuO) were grown in the same batch of crystal development and had practically identical resistivity parameters. It has been established that when the $ReBa_2Cu_3O_{7-\delta}$ (Re = Y, Ho) compounds are saturated with oxygen, the structure transforms from tetragonal to orthorhombic, which in turn, causes the crystal twinning minimizing the elastic energy [4].

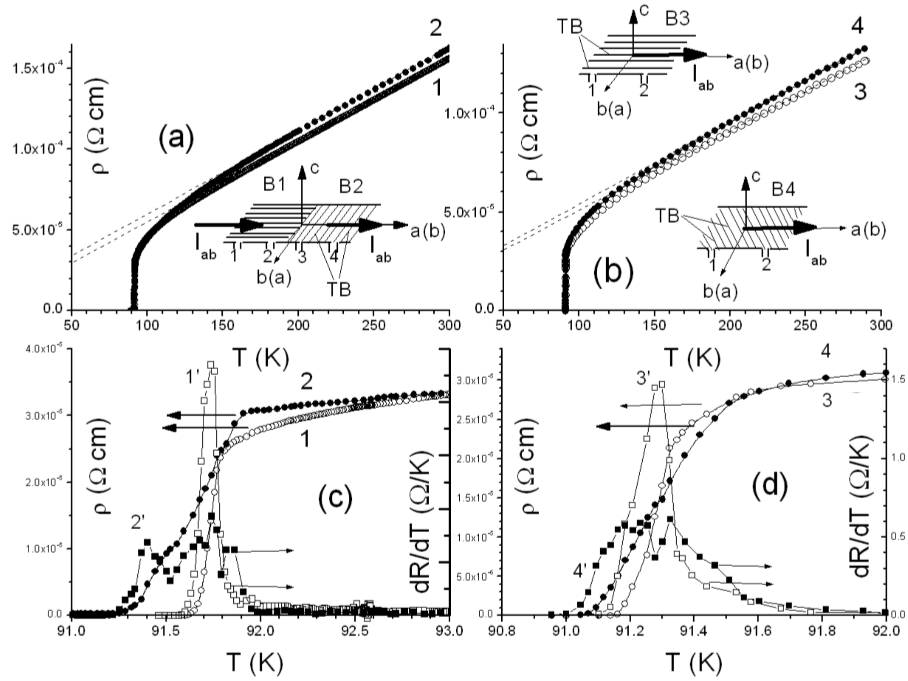

Fig. 1. Temperature dependence of in-plane resistivity $\rho_{ab}(T)$ for bridges B1, B2 (a) and B3, B4 (b) — curves 1–4, respectively. Insets in (a) and (b): schematic representations of the geometry of the experiment. (c) and (d) — resistivity transition into superconducting condition for bridges B1, B2 (c) and B3, B4 (d) in ρ_{ab}–T (curves 1–4, respectively) and $d\rho_{ab}/dT$–T (curves $1'$–$4'$, respectively) coordinates.

For the resistivity measurements single crystals were selected with permeable TB. The area with uniform direction of twin boundaries had dimensions 0.5×0.5 mm^2. The samples were cut from the single crystals and were 0.2 mm wide. The area with uniform direction of twin boundaries bridges had contact spacing of 0.3 mm. The experimental geometry was selected so that the transport current vector, $\boldsymbol{I}$, was either parallel, $\boldsymbol{I} \| \mathrm{TB}$, bridges B1 (K1 sample, YBaCuO) and B3 (K2 sample, HoBaCuO), perpendicular, $\boldsymbol{I} \perp \mathrm{TB}$, B2 (K1 sample, YBaCuO), or at an angle of $\alpha = 45°$, B4 (K3 sample, HoBaCuO) to the twin planes, as is shown in the insets of Fig. 1. All the measurements were conducted under two opposite directions of the transport current to eliminate the impact of the parasitic signal. The high quality of the experimental samples and the homogeneity in oxygen's distribution is proved by the narrow superconducting transition width ($\Delta T_{\mathrm{c}} < 0.5$ K), the high critical temperature ($T_{\mathrm{c}} \approx 92$ K) and the low electrical resistivity ($\rho \approx 120-150$ $\mu\Omega$ cm).

3. Results and discussion

Figure 1 shows the temperature dependence of the electric resistivity in the ab-plane, $\rho_{ab}(T)$, for the analyzed samples illustrating the resistive superconducting transitions in $\mathrm{d}p/\mathrm{d}T - T$ coordinates. According to the procedure from a previous study [3], the maximum position, corresponding to the inflection point, in the dependences is considered as the critical temperature of the resistive superconducting transition. The narrow superconducting transition width ($\Delta T_{\mathrm{c}} < 0.5$ K) shows the high quality of the samples. At the same time, a lower additional peak in the curve, corresponding to $\boldsymbol{I} \perp \mathrm{TB}$ and $\alpha = 45°$ experimental geometries, is possibly due to the effect of twin boundaries, where the ordering parameter is somewhat suppressed [5]. The data obtained for the samples is given in Table.

TABLE

The materials properties determined at different bridges.

Bridge	$T_{\mathrm{c}}^{\mathrm{mf}}$ [K]	ε_0	$\alpha_{3\mathrm{D}}$	$\alpha_{2\mathrm{D}}$	$\xi_{\mathrm{c}}(0)$ [Å]
B1 ($\boldsymbol{I} \| \mathrm{TB}$)	91.738	0.065±0.005	–0.498	–1.017	1.49±0.06
B2 ($\boldsymbol{I} \perp \mathrm{TB}$)	91.743	0.057±0.005	–0.512	–1.044	1.40±0.06
B3 ($\boldsymbol{I} \| \mathrm{TB}$)	91.301	0.103±0.005	–0.489	–0.998	1.88±0.06
B4 ($\alpha = 45°$)	91.325	0.092±0.005	–0.505	–1.015	1.77±0.06

It can be seen from Fig. 1 that the $\rho_{ab}(T)$ dependences are metallic in character for all cases. For the $\boldsymbol{I} \| \mathrm{TB}$ orientation, the resistivity at room temperature is about 5% lower than that for $\boldsymbol{I} \perp \mathrm{TB}$ or $\alpha = 45°$. As the vector $\boldsymbol{I}$ is oriented relative to crystallographic axes in the same manner, the larger ρ_{ab} value at $\boldsymbol{I} \perp \mathrm{TB}$ and $\alpha = 45°$ can be explained by the current carrier scattering at the TB. The electron free path in the single crystals has been estimated to be 0.1 μm [6], this is one order smaller than the twin spacing. The maximum resistance increase due to scattering at the twin boundaries is 10%. Consequently, the observed 5% increase in ρ_{ab} is due to the efficient carrier scattering at the TB.

It follows from Fig. 1 that above 150 K, the temperature dependence of the resistivity is approximately linear. Below 150 K, the resistivity deviates from linearity and there appears an excess conductivity determined by the relation

$$\Delta\sigma = \sigma - \sigma_0, \tag{1}$$

where σ_0 is the conductivity value determined by extrapolating the linear section of $\sigma = (A + BT)^{-1}$ 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 the relationship between the coherence length along the c axis (ξ_c) and the 2D layer thickness (d). When $d < \xi_c$, the interaction between the fluctuating pairs occurs within the whole superconductor volume (3D mode), while at $d > \xi_c$, the interaction is possible only 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] and by Lawrence and Doniach [8]. According to the Lawrence and Doniach model [8], the temperature dependence of FC is described by the following equation:

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

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

Figure 2 shows the temperature dependences of excess conductivity in $\ln\Delta\sigma$–$\ln\varepsilon$ coordinates. It can be observed from Fig. 2 that near T_c, the $\Delta\sigma(T)$ dependence is approximated well by line with slope $\tan\alpha \approx -0.5$, thus yielding evidence of the 3D character of fluctuating superconductivity [1, 7] within this temperature range. As the temperature rises further, the slope of $\ln\Delta\sigma(\ln\varepsilon)$ re-

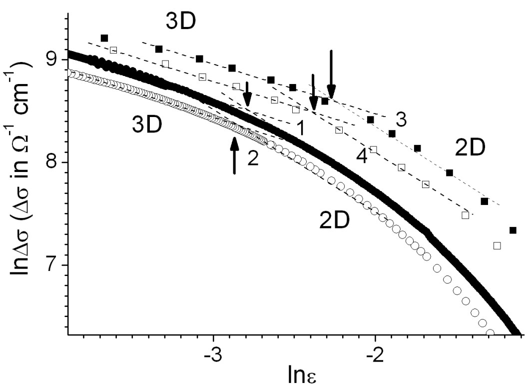

Fig. 2. $\ln\Delta\sigma(\ln\varepsilon)$ dependences for bridges B1–B4 (curves 1–4, respectively). Arrows indicate the 2D–3D crossover points.

lationship increases appreciably. This is an indication of the FC dimensionality change. At the 2D–3D crossover point the following relation must be satisfied [1]:

$$\xi_c(0)\varepsilon^{-1/2} = d/2. \tag{3}$$

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) [9], it is possible to determine $\xi_c(0)$. The results obtained using Eq. (3) as well as the characteristic slope values of the $\ln\Delta\sigma(\ln\varepsilon)$ function are presented in Table. The derived coherence length is in good agreement with the magnetic susceptibility data measured in [4]. Nevertheless, the difference between the $\xi_c(0)$ values for $\boldsymbol{I}\perp$TB, $\alpha = 45°$ and $\boldsymbol{I}\|$TB experimental geometries amounts 6%, thus evidencing an effective influence of TB on the formation processes of the fluctuating Cooper pairs.

It should be noted that this calculation procedure does not take into consideration the possible error in the resistivity measurements when determining the fluctuating quantities in spatially inhomogeneous systems, associated with the small inclusions of other phases even in high-quality single crystals [5]. Therefore, when comparing with experimental data, $\xi_c(0)$ and d in Eqs. (2), (3) are usually considered to be fitting parameters. A scaling factor (C-factor) is also introduced to make it possible to take into account the transport current distribution inhomogeneity in each specific sample [1].

Using the calculation procedure the experimental data are described by the Lawrence and Doniach model (Eq. (2)). In this case, the coherence length $\xi_c(0)$ is 1.7 ± 0.3 Å, 1.9 ± 0.3 Å for the bridges B2, B1 and 2 ± 0.3 Å, 2.2 ± 0.3 Å for the bridges B4, B3, respectively. The derived coherence length is in good agreement with the magnetic susceptibility data measured in [9] where the ξ_c value obtained was $\xi_c = 2.3 \pm 0.5$ Å, 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 $\boldsymbol{I}\perp$TB, $\alpha = 45°$ and $\boldsymbol{I}\|$TB experimental geometries amounts 6% to 12%, thus evidencing an effective influence of TB on the formation processes of the fluctuating Cooper pairs.

In summary, the resistance increase within the linear section of $\rho(T)$ shows dependences between the transport current perpendicular $\boldsymbol{I}\perp$TB as compared to the case of $\boldsymbol{I}\|$TB and it is due to an efficient scattering of normal carriers at the TB. The excess conductivity functions, $\Delta\sigma(T)$, are well described by the Lawrence–Doniach theoretical model. The presence of twin boundaries in the crystal sustains 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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