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Room-temperature annealing effects on the basal-plane resistivity of optimally doped $YBa_2Cu_3O_{7-\delta}$ single crystals

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ABSTRACT

We reveal that the temperature dependence of the basal-plane normal-state electrical resistance of optimally doped $YBa_2Cu_3O_{7-\delta}$ single crystals can be with great accuracy approximated within the framework of the model of s-d electron-phonon scattering. This requires taking into account the fluctuation conductivity whose contribution exponentially increases with decreasing temperature and decreases with an increase of oxygen deficiency. Room-temperature annealing improves the sample and, thus, increases the superconducting transition temperature. The temperature of the 2D-3D crossover decreases during annealing.

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1. Introduction

Long-term stability of the electrical transport characteristics of modern multipurpose materials based on high-T_c superconducting cuprates is one of the most crucial requirements for their use in instruments and devices. Thus far, one of the most asked-for compounds is the so-called 1-2-3 system $RBa_2Cu_3O_{7-\delta}$ (where R = Y or other rare earths) [1,2]. This is stipulated by several important factors. Firstly, this compounds have rather high critical characteristics, namely the superconducting transition temperature $T_c > 90$ K, noticeably above the nitrogen liquefaction temperature. Secondly, one can rather easily vary both, the superconducting and normal-state characteristics of the system by complete or a partial substitution of its constituents or changing the deviation degree from the oxygen stoichiometry [3]. Finally, there are well-established technologies for the fabrication of cast, thin-film and single-crystal samples of rather big sizes, the latter being especially favorable for fundamental investigations.

At the same time, the presence of a labile component (oxygen) in the compound leads to the appearance of a nonequilibrium state in a particular sample. The latter can easily be induced by the application of a high pressure [4], an abrupt temperature change [5], or ensue in the course of a long-term storage or exploitation (aging) [6]. Thus far, rather specific diffusion processes take place in the system [7] that, in turn, contributes to a phase segregation [8], structural relaxation, and the appearance of various superstructures. All these factors noticeably affect the charge and heat transfer mechanisms in the system, as well as the appearance of peculiar electrical transport phenomena such as fluctuation conductivity [9], pseudogap anomaly [10], incoherent electronic transport [11] and so on. According to contemporary views, it is these nontrivial phenomena in the normal state which are expected to be the key to understanding the microscopic nature of high-T_c superconductivity which remains unresolved so far, despite a more than 30-year-long history of intensive experimental and theoretical investigations.

The electrical properties of superconducting cuprates in the normal state are known to differ not much from those of ordinary metals, see e.g. Ref. [12]. It was shown that the experimental dependences of the basal-plane electrical resistance of underdoped $YBa_2Cu_3O_{7-\delta}$ single crystals in the normal state, $\rho_{nab}(T)$, can be described well by the Bloch–Grüneisen formula [12] accounting for scattering of the conduction electrons on phonons and defects. In this case the dependence $d\rho_{nab}(T)/dT$ exhibits a smeared maximum at $T_m \approx 0.35\theta$, where θ is the Debye temperature amounting to $\theta \simeq 500$ K for underdoped samples. Accordingly, $\rho_{ab}(T)$ has a characteristic inflection peculiar to phonon scattering. At $T > \theta$ the Bloch–Grüneisen expression asymptotically tends to a straight line with increasing temperature, while with a decrease of the temperature it turns down from the high-temperature extrapolation $\rho \propto T$, that is associated with a transition from elastic to inelastic phonon scattering.

For optimally doped $YBa_2Cu_3O_{7-\delta}$ single crystals there is no maximum in $d\rho_{nab}(T)/dT$ that might be stipulated by a decrease of T_m to $T_m \leq T_c$, that is by a decrease of θ to $\theta \leq 200$ K. It is

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worth noting that (i) phonon scattering always takes place and (ii) the resistivity values of $YBa_2Cu_3O_{7-\delta}$ single crystals correspond to those of metal systems with a pseudogap, such as amorphous alloys, quasicrystals, transition metal dichalcogenides and so on [13]. A downturn of $\rho_{nab}(T)$ from $\rho \propto T$ may also be caused by an excess conductivity which has an exponential increase with decreasing temperature and is associated with the pseudogap in $YBa_2Cu_3O_{7-\delta}$.

Thus, in order to approximate the dependence $\rho_{ab}(T)$ of $YBa_2Cu_3O_{7-\delta}$ single crystals in a wide temperature range it is necessary to take into account the various mechanisms of the conductivity and charge carriers scattering. In the present work, we study the effect of annealing at room temperature on the approximation parameters and on the superconducting characteristics of the samples — the point which has insufficiently been investigated in the literature so far. This makes it possible to clarify the physical nature of the individual conduction and scattering mechanisms, as well as the ways to affect them.

2. Experimental

The $YBa_2Cu_3O_{7-\delta}$ single crystals were grown by the solution-melt technique in a gold crucible as in Ref. [14]. As it is known [14], a tetra-ortho structural transition takes place in $YBa_2Cu_3O_{7-\delta}$ upon saturation with oxygen. This transition leads to a crystal twinning thus minimizing its elastic energy. To obtain twin-free samples, crystals were untwinned in a crucible at a pressure of 30 – 40 GPa at 420°C as described in Ref. [15]. To obtain a controllable homogeneous distribution of oxygen, the samples were further annealed in an oxygen atmosphere at 420°C for 7 days.

For resistive measurements several crystals were selected. Electrical contacts were created in the standard 4-probe geometry by applying a silver paint on the crystal surface. This followed by attachment of silver conductors with 0.05 mm in diameter and a three-hour-long annealing at 200°C in ambient atmosphere. This procedure has allowed us to obtain a transient contact resistance of less than 1 Ω and to conduct resistance measurements at transport currents up to 10 mA in the *ab*-plane. The measurements were done in the temperature-sweep mode. Temperature was measured using a platinum resistor thermometer. The superconducting transition temperature was determined at the point of maxima in the dependences $d\rho_{ab}(T)/dT$ in the region of the superconducting transition.

To reduce the oxygen content, the samples were annealed in an oxygen flow at 620°C for two days. After annealing the samples were quenched to room temperature within 2 – 3 min., mounted on the holder, and cooled down to liquid nitrogen temperatures within 10–15 min. All measurements were done while warming the samples up. For investigations of the effect of room-temperature annealing, after the first measurement of $\rho(T)$, the samples were kept at room temperature for 20 h and repetitive measurements were performed. The final series of measurements was done after a room-temperature annealing of the samples for 3 days. In what follows we discuss the data acquired on one typical sample.

3. Results and discussion

3.1. Normal resistance and excess conductivity

Fig. 1 displays the experimental temperature dependence of the basal-plane electrical resistivity, ρ_{ab}, (symbols) of the optimally doped $YBa_2Cu_3O_{7-\delta}$ single crystal after quenching from 620°C. The curves measured after different stages of annealing are qualitatively similar. The dependence $\rho_{ab}(T)$ has been revealed to fit (solid line in Fig. 1) the Bloch–Grüneisen formula

$$\rho_{app}(T) = [\rho_n^{-1}(T) + b_0(\exp^{T_1/T} - 1)]^{-1}, \tag{1}$$

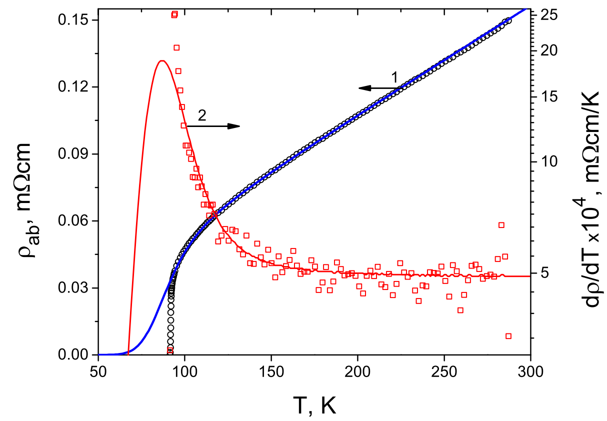

Fig. 1. Temperature dependences of the electrical resistivity $\rho_{ab}(T)$ of the optimally doped $YBa_2Cu_3O_{7-\delta}$ single crystal after quenching from 620°C. 1 – $\rho_{ab}(T)$. Symbols: experiment. Solid line: Calculation by Eqs. (1) and (2). 2 - $d\rho_{nab}(T)/dT$. Symbols: Evaluated experimental data. Solid line: calculation by Eqs. (1) and (2).

Table 1
Fitting parameters for the basal-plane electrical resistivity of the optimally doped $YBa_2Cu_3O_{7-\delta}$ single crystal by Eqs. (1)–(3).

	Quenching from 620°C	Annealing for 20 h	Annealing for 92 h
ρ_0, mΩcm	0.0126	0.0119	0.0140
C_3, mΩcm	0.141	0.134	0.134
θ, K	145	138	142
$T_1 = U_{pg}/k$, K	1060	1060	1070
b_0, $(\text{m}\Omega\text{cm})^{-1}$	1.05×10^{-4}	1.06×10^{-4}	9.9×10^{-5}
T_c, K	91.88	91.95	92.01
$\Delta T_{c0.5}$, K	0.366	0.325	0.233
T_{cross}, K	92.09	92.05	≥ 92.01
$\xi_c(T_{cross})$, Å	0.28	0.25	–

where

$$\rho_n(T) = \rho_0 + C_3\left(\frac{T}{\theta}\right)^3 \int_0^{\theta/T} \frac{e^x x^3 dx}{(e^x - 1)^2}, \tag{2}$$

and ρ_0 is the residual resistivity. The fitting parameters in Eqs. (1) and (2) were determined by minimums of the error least squares, which does not exceed 1%. The fitting parameters are reported in Table 1.

Fig. 1 also displays the temperature dependences of the derivative $d\rho_{nab}(T)/dT$ (symbols) and the temperature derivative of Eq. (1) (solid line). Due to the presence of the exponential term in Eq. (1) the maximum in $d\rho_{app}(T)/dT$ ensues at $T_m \approx 87$ K, while the maximum in $d\rho_n(T)/dT$ at $T_{mBG} \approx 50$ K.

We note that at $T \gg \theta$ it is $\rho_n \approx \rho_0 + \left(\frac{C_3}{2\theta}\right)T$ which yields the mentioned linear temperature dependence $\rho_{ab}(T)$ at high temperatures, namely at $T \geq 170$ K in our case.

The relative changes of the fitting parameters for Eqs. (1) and (2) in dependence on the time of annealing at 20°C are presented in Fig. 2. One sees that for the optimally doped $YBa_2Cu_3O_{7-\delta}$ single crystal the 92 h-long room-temperature annealing does not lead to significant changes in the parameters of charge scattering on phonons. Namely, the phonon scattering coefficient C_3 and the Debye temperature θ only exhibit a weak tendency to increase. We note that the Debye temperature for optimally doped single crystals is much smaller than for underdoped ones in a reference measurement. Since the crystal lattice of $YBa_2Cu_3O_{7-\delta}$ is easily deformed under the relative shift of the layers, and $\theta \propto a^{-1}$ (*a* is the interatomic distance), the small values of θ obtained by approximating the temperature dependence of the resistance of a perfect single crystal can be due to the preferential charge carriers scattering on the vibrations of atoms along the *c* axis ($\theta \propto d^{-1}$, *d* is

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