Functional Materials 21, No.2 (2014)

Scattering of electrons in oxygen underdoped $YBa_2Cu_3O_{7-x}$ single crystals

G.Ya.Khadzhai, R.V.Vovk, N.R.Vovk

V.Karazin National University,
4 Svoboda Sq., 61022 Kharkiv, Ukraine

Received October 31, 2013

The electrical resistivity in the range of T_c–300 K in the layer planes of $YBa_2Cu_3O_{7-x}$ single crystals with a range of oxygen deficiency, which is characterized by the T_c in the range 78 ÷ 92 K was studied. The experimental data on the resistance in normal state are approximated by an expression that takes into account the scattering of electrons on phonons, as well as on defects and the fluctuation conductivity in 3D-model of the Aslamazov-Larkin theory. According to this approximation, depending upon the oxygen deficiency, the Debye temperature changes from 245 to 400 K, coherence length $\xi_c(0) \approx 0.5$ Å.

В интервале T_c–300 К исследовано электросопротивление в плоскости слоев монокристаллов $YBa_2Cu_3O_{7-x}$ высокой степени совершенства с различным дефицитом кислорода, обеспечивающим изменение T_c от 78 до 92 К. Экспериментальные данные аппроксимированы выражением, учитывающим рассеяние электронов на фононах, дефектах, а также флуктуационную проводимость в 3D-модели Асламазова-Ларкина. По данным аппроксимации, в зависимости от дефицита кислорода температура Дебая изменяется в пределах 245 ÷ 400 К, $\xi_c(0) \approx 0.5$ Å.

Розсіювання електронів в недодопованих киснем монокристалах $YBa_2Cu_3O_{7-x}$. *Г.Я.Хаджай, Р.В.Вовк, М.Р.Вовк.*

В інтервалі T_c–300 К досліджено електроопір у площині шарів монокристалів $YBa_2Cu_3O_{7-x}$ високого ступеня досконалості з різним дефіцитом кисню, що забезпечує зміну T_c від 78 до 92 К. Експериментальні дані апроксимовані виразом, що враховує розсіювання електронів на фононах, дефектах, а також флуктуаційну провідність у 3D-моделі Асламазова-Ларкіна. За даними апроксимації, залежно від дефіциту кисню температура Дебая змінюється у межах 245 ÷ 400 К, $\xi_c(0) \approx 0.5$ Å.

1. Introduction

The explanation of the conduction mechanisms and the charge carriers' scattering in high-temperature superconductors (HTSC), near the critical temperature as well as in the normal state, is useful to understand the nature of high-temperature superconductivity. The issues regarding the realization of different modes of the fluctuation pairing of carriers is actively studied since the early stages of the research of the HTSC [1–5]. With a decrease in the oxygen concentration, the electrical resistance of $YBa_2Cu_3O_{7-x}$ compounds increases and the critical temperature (T_c) decreases [6–11]. In that respect the structure and the topology of the defect assembly [12–15] and the extent and the nature of the labile oxygen ordering of the subsystem is important [16–19]. Notably, despite the rather extensive experimental data, the question of the influence of small oxygen deficiency on the different conduction regimes and, in particular, on the fluctuation conductivity (FC) of these compounds, is still not completely understood. This is probably, due to the fact that most of the available experimental data was obtained on ceramic samples with a high content of intergranular bonds, as well as on films deposited on substrates of different types, through different processes [1–3, 20]. Therefore, the study of the evolution of different modes of fluctuation conductivity in $YBa_2Cu_3O_{7-x}$ single crystals is very important. In these highly pure compounds, it is possible to carry out measurements in a controlled manner, so that by varying the concentration of oxygen we could vary the scattering and conductivity parameters [4, 7, 11, 17].

In HTSC of the high degree of perfection and with the optimal oxygen content at high temperatures ($T \geq \theta$, θ the Debye temperature) is often observed an almost linear temperature dependence of the resistivity, which is naturally associated with the scattering of electrons by phonons (see, for example, [21]). With decreasing temperature the phonon resistance deflected downward from the high-T_c extrapolation ($\rho \infty T$) even at $T \leq \theta/3$ [18], where it can be also shown and fluctuation conductivity. Therefore it is difficult to divide experimentally the region where the metallic conductivity, limited by scattering on phonons, exists and the region of fluctuation conductivity existing.

2. Experimental

The $YBa_2Cu_3O_{7-x}$ single crystals were grown by solution-melt method in a gold crucible at a temperature range between 850–970°C, as described in detail in [4, 14]. The typical sample size is $2\times0.3\times0.02$ mm^3. The smallest size corresponded to the c axis. To take samples with near optimal oxygen concentration, $\delta \leq 0.1$, the selected crystals were annealed in oxygen flow at 400°C for five days. To reduce the oxygen content, the samples were annealed for three to five days in oxygen flow at higher temperatures. The electrical contacts were made from silver conductors, which were connected to the crystal surface with a silver paste. Measurements of electrical resistance were performed in the layers' plane by the standard four-contact method at a constant current of 1 mA in the two opposite directions of the current at a zero magnetic field. The geometry of the sample was such that the transport current vector was oriented at an angle 45° relative to the twin boundaries (TB) planes. The temperature was measured by a copper-constantan thermocouple, the voltage in the sample, by the nanovoltmeters B2-38. Measurements were carried out in the mode of temperature drift, which was about 0.1 K/min for measurements near T_c and about 5 K/min at $T > T_c$. Thus, all the measurements were performed three days later, after the annealing, which provided the equilibrium distribution of oxygen within the volume of the sample at room temperature [8, 9].

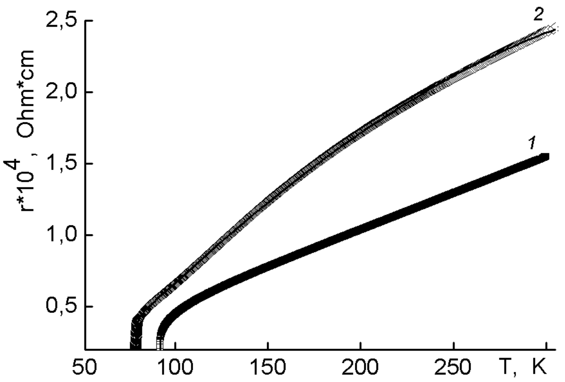

Fig. 1. The temperature dependences of the resistivity of $YBa_2Cu_3O_{7-x}$ single-crystal. The points are the experimental data, the curves shows the approximation by (1)–(2). 1 — Tc = 91.732 K, 2 — Tc = 78.591 K. The results for intermediate values of T_c are not shown for simplicity (see Table).

3. Results and discussion

The temperature dependences of the resistivity for different oxygen concentrations are shown in Fig. 1.

We approximate the temperature dependence of the resistivity in the samples in the range T_c–300 with an expression that takes into account the scattering of electrons by phonons (s–d processes) [22], defects, and the fluctuation conductivity, with the smallest error is the use of the latest 3D-model Aslamazov-Larkin [23]. Therefore, the general expression for the conductivity is expressed by the form:

$$\sigma = \rho_{sc}^{-1} + \Delta\sigma_{AL}; \qquad (1)$$

$$\rho_{sc} = (\rho_0 + \rho_3)\cdot(1 - b_0 \cdot T^2);$$

$$\rho_3 = C_3\left(\frac{T}{\theta}\right)^3 \int_0^{\theta/T} \frac{x^n e^x}{(e^x - 1)^2}dx.$$

Here ρ_0 is the residual resistance that characterizes the scattering to the defects; ρ_3 is the contribution to the resistance due to inter-band (s–d processes) scattering to the

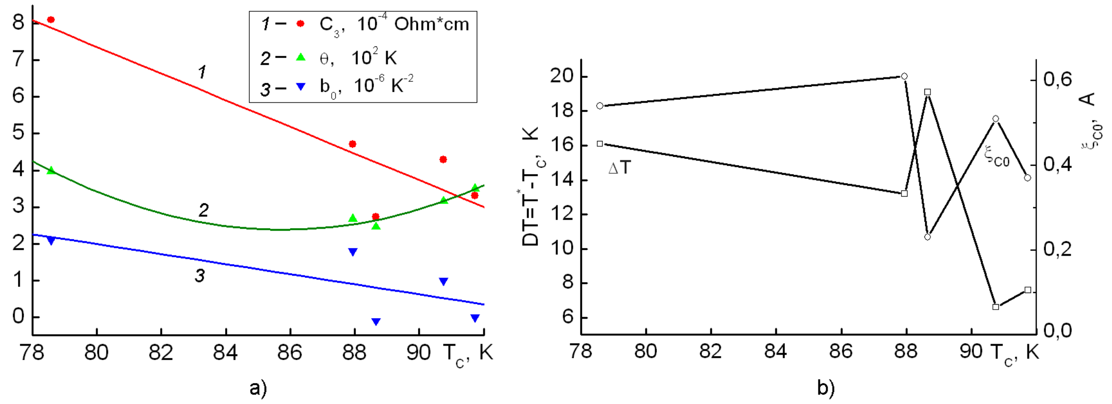

Fig. 2. a) The dependences of the approximation parameters from T_c for the phonon scattering: *1* — C_3, 10^{-4} Ohm·cm; *2* — θ, 10^2 K; *3* — b_0, 10^{-6} K^{-2}; (b) The dependences of the approximation parameters from T_c for the fluctuation conductivity.

phonons; θ is the Debye temperature; b_0 depends on the shape of the electron density of states, effective mass of the carriers and the Fermi energy [24,25].

$$\Delta\sigma_{AL} = e^2/(16\hbar\xi_c(0)2\varepsilon_0\sinh(\varepsilon/\varepsilon_0)). \qquad (2)$$

Such an expression for the fluctuation conductivity is chosen to limit the area of its influence [26], $\varepsilon = \ln[(T - T_c)/T_c]$ is the reduced temperature, T_c is the critical temperature in the mean-field approximation, $T > T_c$, $\xi_c(0)$ is the coherence length, ε_0 determines the temperature range of superconducting fluctuations $\varepsilon_0 = \ln(T^*/T_c)$, T^* is the characteristic temperature, which describes — together with the $\xi_c(0)$ — the collapse of the superconducting fluctuations.

The best parameter set of the approximations that provides an average error of about 1 % over the interval of T_c–300 K is shown in Table together with data on oxygen deficiency, δ, taken from the $T_c(\delta)$ [27–29]. Approximating curves shown in Fig. 1 with solid lines.

Figure 2 shows the dependence of the approximation parameters from T_c. In Fig. 2a, the parameters of the phonon scattering and in Fig. 2b, the parameters of the fluctuation conductivity are shown. The Table shows that the residual resistance, ρ_0, is practically independent from the T_c. This is due to a high error in the determination of the residual resistance by extrapolation: $\rho_0 = \rho_{sc}(T \to 0)$. Furthermore, it may also affect the spatial heterogeneity associated with the presence of small inclusions of a different phase, even in high-quality single crystals [24]. The values of the Debye temperature, θ, correspond to the literature (for example [30]).

Fig. 2a shows, that with the increase of T_c, the parameters C_3 and b_0 are reduced. In the same time, the Debye temperature, θ, passes through a minimum in the interval of $T_c \approx 84$–86 K. This change in the Debye

Table. Experimental and approximation parameters of the temperature dependence of the resistivity, using the Eq.(1)

T_c, K	91.732	90.748	88.656	87.942	78.591
δ [9–11]	0.1510	0.160	0.177	0.181	0.237
ρ_0, Ohm·cm	$2\cdot10^{-5}$	$1\cdot10^{-5}$	$3\cdot10^{-5}$	$6\cdot10^{-7}$	$1.4\cdot10^{-5}$
C_3, Ohm·cm	$3.315\cdot10^{-4}$	$4.285\cdot10^{-4}$	$2.725\cdot10^{-4}$	$4.715\cdot10^{-4}$	$8.1\cdot10^{-4}$
θ, K	349.5	316.5	245.5	268	398.5
B_0, K^{-2}	0	$1\cdot10^{-6}$	$-1\cdot10^{-7}$	$1.8\cdot10^{-6}$	$2.1\cdot10^{-6}$
$\xi_c(0)$, Å	0.37	0.51	0.23	0.61	0.54
ε_0	0.08	0.07	0.195	0.14	0.19
$\Delta T = T^* - T_{\text{Б}}$					

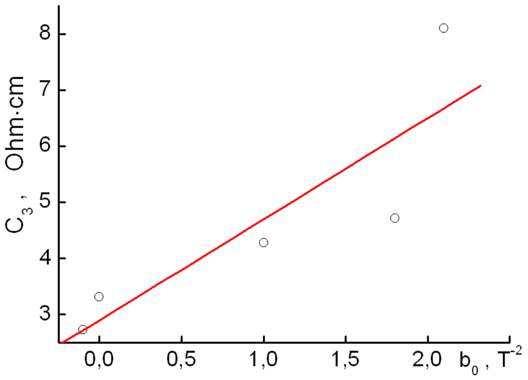

Fig. 3. The ratio between C_3 and b_0.

temperature is probably associated with the Ortho-I-Ortho-II transition and, accordingly, with the changes in the type of the oxygen superstructure in the concentration interval $\delta \approx 0.17–0.18$ [27, 29]. Note that near the maximum T_c (88–92 K), the Debye temperature, θ, increases by the T_c, increase, i.e by decreasing the δ. This means that the closer to the stoichiometric composition leads to a decrease in the crystal lattice parameters of $YBa_2Cu_3O_{7-x}$. Parameters C_3 and b_0 are determined by the electronic structure of the sample, in particular, by the Fermi energy and the density of states. So the correlation between them is natural (Fig. 3).

Fig. 2b shows the dependence of the average coherence length $\xi_c(0)$ from T_c and the temperature range of superconducting fluctuations, $\Delta T = T^* - T_c$. It can be seen that when the T_c increases these parameters show a slight tendency to decrease. The fact that the coherence length was less than the interlayer distance, corresponds to the literature data [1, 31] and indicates the necessity to consider at least three factors. First, the spatial heterogeneity associated with the presence of another phase [24] and causing uneven distribution of the current through the sample, which theoretically cannot take into account. Second, it is the 2D → 3D crossover, which takes place near the T_c. Finally, it is the possible impact of specific mechanisms of quasiparticle scattering [32–36], which can be due to the presence of structural and kinematic anisotropy in the system.

4. Conclusions

The experimental data of high-quality $YBa_2Cu_3O_{7-x}$ single crystals regarding the electrical resistance in the temperature interval T_c–300 K can be approximated by taking into account the electron scattering on phonons and defects and the fluctuation conductivity in the form of a 3D-model of the Aslamazov-Larkin theory. The approximation parameters are quite reasonable, but a more adequate description requires consideration the 2D → 3D crossover and, if necessary, the multiphase structure of the sample.

References

1. T.A.Friedman, J.P.Rice, J.Giapintzakis, D.M.Ginzberg, *Phys.Rev.B*, **39**, 4258 (1989).
2. N.E.Alexeevskii, A.V.Mitin, E.P.Khlybov et al., *Supercond.:Phys.Chem.Eng.*, **2**, 40 (1989).
3. H.A.Borges, M.A.Continentino, *Solid State Commun.*, **80**, 197 (1991).
4. M.A.Obolenskii, R.V.Vovk, A.V.Bondarenko, N.N.Chebotaev, *Low Temp. Phys.*, **32**, 571 (2006).
5. R.V.Vovk, M.A.Obolenskii, A.A.Zavgorodniy, A.V.Bondarenko, *J. Alloys Comp.*, **453**, 69 (2008).
6. P.Schleger, W.N.Hardy, B.X.Yang, *Physica C*, **176**, 261 (1991).
7. R.V.Vovk, N.R.Vovk, A.V.Samoilov et al., *Solid State Commun.*, **170**, 6 (2013).
8. A.V.Bondarenko, V.A.Shklovskij, R.V.Vovk et al., *Low Temp. Phys.*, **23**, 962 (1997).
9. R.V.Vovk, M.A.Obolenskii, A.A.Zavgorodniy et al., *Physica C*, **469**, 203 (2009).
10. S.Sadewasser, J.S.Schilling, A.P.Paulicas, B.M.Veal, *Phys.Rev.B*, **61**, 741 (2000).
11. R.V.Vovk, A.A.Zavgorodniy, M.A.Obolenskii et al., *J. Mater. Sci.: Mater. in Electron.*, **22**, 20 (2011).
12. A.V.Bondarenko, V.A.Shklovskij, M.A.Obolenskii et al., *Phys. Rev. B — Condens. Matter and Mater. Phys.*, **58**, 2445 (1998).
13. R.V.Vovk, M.A.Obolenskii, Z.F.Nazyrov et al., *J. Mater. Sci.: Mater. in Electron.*, **23**, 1255 (2012).
14. A.V.Bondarenko, A.A.Prodan, M.A.Obolenskii et al., *Low Temper. Phys.*, **27**, 339 (2001).
15. R.V.Vovk, N.R.Vovk, O.V.Shekhovtsov et al., *Supercond.Sci.Technol.*, **26**, 085017 (2013).
16. J.D.Jorgencen, P.Shiyou, P.Lightfoot et al., *Physica C*, **167**, 571 (1990).
17. R.V.Vovk, Z.F.Nazyrov, M.A.Obolenskii et al., *Philosoph. Mag.*, **91**, 2291 (2011).
18. R.V.Vovk, G.Ya.Khadzhai, Z.F.Nazyrov et al., *Physica B*, **407**, 4470 (2012).
19. R.V.Vovk, A.A.Zavgorodniy, M.A.Obolenskii et al., *Modern Phys. Lett. B*, **24**, 2295 (2010).
20. P.Rodriges, A.R.Jurelo, P.de Azambuja, *Modern Phys. Lett. B*, **22**, 1717 (2008).
21. E.G.Maximov, *Uspekhi Fiz.Nauk*, **170**, 1033 (2000).
22. L.J.Colquitt, *Appl.Phys.*, **36**, 2454 (1965).
23. L.G.Aslamazov, A.I.Larkin, *Phys.Lett.*, **26A**, 238 (1968).
24. T.Aisaka, M.J.Shimizu, *Phys.Soc.Jpn.*, **28**, 646 (1970).

25. U.Schwingenschlogl, C.Scuster, *Appl.Phys. Lett.*, **100**, 253111 (2012).
26. B.Leridon, A.Defossez, J.Dumont et al., *Phys. Rev.Lett.*, **87**, 197007-1 (2001).
27. T.Krekels, H.Zou, G.Van Tendeloo et al., *Physica C*, **196**, 363 (1992).
28. Liang Ruixing, D.A.Bonn, W.N.Hardy, *Physica C*, **304**, 105 (1998).
29. Liang Ruixing, D.A.Bonn, W.N.Hardy, *Phys. Rev. B*, **73**, 180505 (2006).
30. Alekseevskii N.E., Gusev A.V., Devyatykh G.G. et al., *JETP Lett.*, **47**, 168 (1988).
31. B.Oh, K.Char, A.D.Kent, Naito M. et al., *Phys.Rev.B*, **37**, 7861 (1988).
32. R.V.Vovk, C.D.H.Williams, A.F.G.Wyatt, *Phys.Rev.B*, **69**, 144524 (2004).
33. A.J.Matthews, K.V.Kavokin, A.Usher et al., *Phys.Rev.B*, **70**, 075317 (2004).
34. A.J.Matthews, P.G.Curran, V.V.Khotkevych et al., *Phys.Rev.B*, **84**, 104507 (2011).
35. D.H.C.Smith, R.V.Vovk, C.D.H.Williams, A.F.G.Wyatt, *New J. Phys.*, **8**, 128 (2006).
36. I.N.Adamenko, K.E.Nemchenko, V.I.Tsyganok, A.I.Chervanev, *Low Temp.Phys.*, **20**, 498 (1994).