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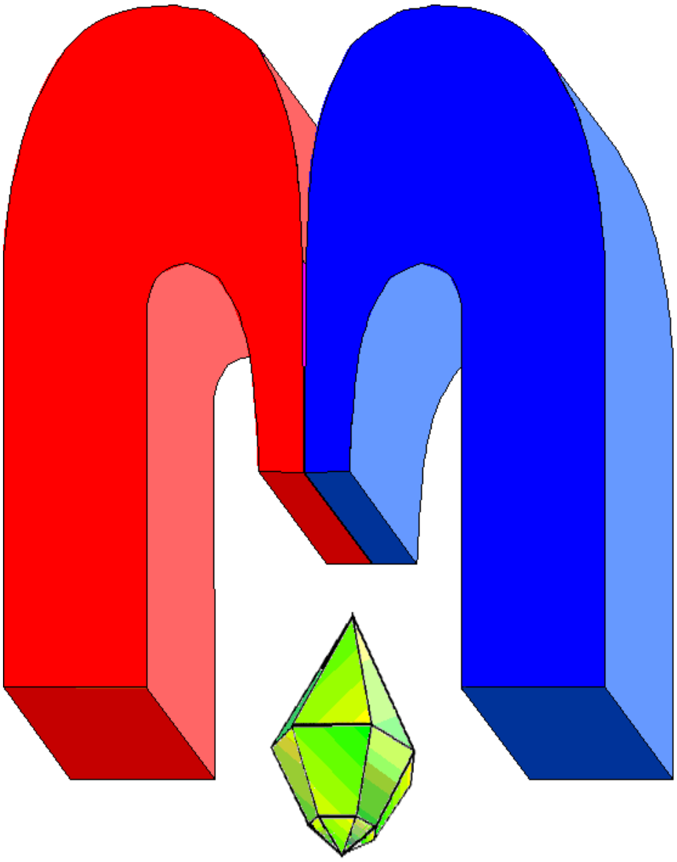

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[*] In Kazan University the Electron Paramagnetic Resonance (EPR) was discovered by Zavoisky E.K. in 1944.

Superconducting fluctuations above critical temperature in the $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_8$ single crystals[†]

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The superconducting fluctuations above critical temperature in the $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_8$ single crystals are studied. The boundaries of the superconducting fluctuations area are defined by the MWA measurement. The estimation of the fluctuations lifetimes is made.

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1. Introduction

The pseudogap state of high temperature superconductors (HTS) are studied extensively at the present time in many laboratories around the world. The relevance of the problem is that it is impossible to determine the mechanism of high-temperature superconductivity without understanding the nature of the pseudogap. This in turn constrains the progress of improving the critical parameters of HTS materials. Particular attention is paid to the area of phase diagram, which borders with the superconducting region. In this region the influence of the fluctuations of superconducting order parameter (SOPF) has a great effect on all the electronic and magnetic properties. Their influence is revealed with some tools such as tunneling spectroscopy (see for example [1]), the measurements of the Nernst effect [2] and so on. The study have shown SOPF survived in unusually large temperature range (tens Kelvins) over the critical temperature T_c. Sometimes their effect is comparable with that of the superconducting state, in particular in great Nernst effect [2]. It is tempting to suggest that one can broaden the superconducting region by the way of the increase of the fluctuation lifetime.

Therefore information about fluctuations, such as character, spatial sizes and lifetimes, is well useful for the creation of the SOPF clear picture and for finding the method of their control. Data obtained using the tunneling microscopy and the Nernst measurements show that the gap in the energy spectrum exists at temperatures above the critical temperature and the state has a vortex character here. The latter assumption is not supported by all researchers. Its verification calls for further investigation with the help of new methods providing otherwise view of problem. As such method we propose to use the measurement of the non-resonant microwave

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absorption (MWA). It performed well at investigation of such magnetic excitations as vortices in superconductors [3].

The main goal of this paper is to obtain additional information about the SOPF in order to improve the understanding the HTS state above T_c. We reveal the superconducting fluctuations and estimate their parameters using the MWA method together with the data of the AC-susceptibility measurement.

2. Experimental

The samples studied were the $\mathrm{Bi_2Sr_2CaCu_2O_8}$ (Bi2212) single crystals doped with yttrium, $\mathrm{Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}}$. Substitution of calcium with yttrium allows us to change the density of charge carriers (holes) p. Varying the Y concentration x from 0 to 0.3 we put samples overdoped with holes ($x = 0$, $p \approx 0.19$), optimally doped one ($x = 0.1$, $p \approx 0.16$), and and two underdoped samples ($x = 0.2$, $p \approx 0.12$; $x = 0.3$, $p \approx 0.07$). In doing so, the superconducting transition temperature varies in the range from 25 to 96 K. Single crystal samples have the shape of a thin plate with the typical size $\sim 3 \times 2 \times 0.1\,\mathrm{mm}^3$.

The main tool for the detection and study of superconducting fluctuations in our work is the measurement of the non-resonant microwave absorption (MWA) upon variation of the temperature or magnetic field. The method allows one to reveal any sort of magnetic objects, such as magnetic particles and magnetic perturbations (for example, magnetic or superconducting vortices). As these measurements are performed at a high frequency ($\sim 10^{10}$ Hz), the possibility to observe the short-living excitations is appeared. In order to determine the superconducting transition temperature T_c and to support the MWA data analysis, we use measurements of magnetic AC susceptibility.

In our work, the EPR spectrometer BRUKER BER-418s of X-band ($\sim$9.3 GHz) was used to measure MWA. In this spectrometer, the use of magnetic modulation and synchronous amplification allows one to enhance significantly the signal-to-noise ratio. In order to obtain a strictly constant magnetic field required for our experiments and to hold the advantage of the lock-in signal detection we use the modulation of the microwave field amplitude instead of the applied magnetic field modulation. The modulation of the incident microwave field realized through P-I-N-diode embedded into the waveguide connecting the microwave source (klystron) with a cavity resonator. A sample placed in the resonator so that its ab crystal plane was parallel to the direction of the microwave field H_1. The direction of the applied magnetic field $H_0 = 5$ Oe was perpendicular to the crystal ab plane. The temperature is varied from 300 K to transition to the superconducting state using helium flow cryostat. The sample temperature was monitored using a thermocouple Cu-Cu:Fe.

The MWA data obtained are compared with the results of the AC-susceptibility measurement. This allows us to find the border of the superconducting area ($T_c(p)$) at the phase diagram and to extract the superconducting fluctuation contribution. The AC-susceptibility measured at a frequency of 1370 Hz with the coil system described in Ref. [4]. Measurements were performed upon cooling a sample from the room temperature down to 10 K in the constant magnetic field $H_0 = 5.8$ Oe applied perpendicular to the crystal ab plane.

3. Results and discussions

We investigated 4 single-crystal samples of $\mathrm{Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}}$ with different hole concentration p, namely overdoped (OD, $p \approx 0.19$) and optimally-doped (OP, $p \approx 0.16$) ones and two underdoped samples with $p \approx 0.12$ (UD1) and $p \approx 0.07$ (UD2).

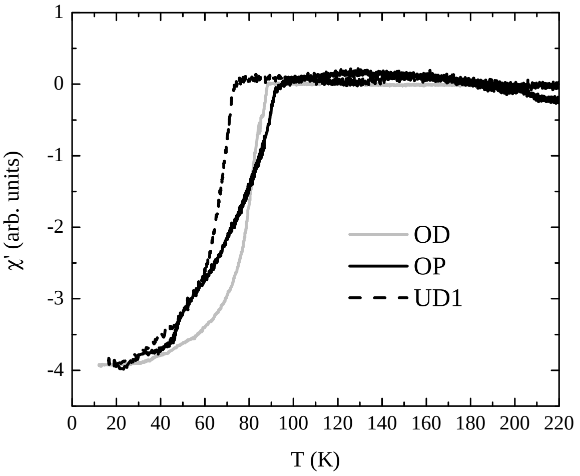

Figure 1. Temperature dependence of the AC susceptibility for samples with different carrier density. AC frequency is 1.37 kHz, applied magnetic field 5.8 Oe is perpendicular to the crystal *ab* plane.

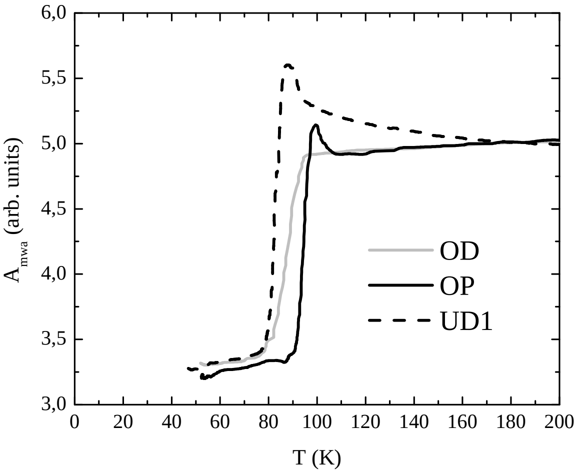

Figure 2. Temperature dependence of MWA for samples with different hole density. The absorption was measured in the applied magnetic field $H_0 = 5$ Oe perpendicular to the crystal *ab* plane.

The hole density was estimated from the T_c value via the empirical equation [5]:

$$T_c/T_{c,\,\mathrm{max}} = 1 - 82.6(p - 0.16)^2. \tag{1}$$

Here $T_{c,\,\mathrm{max}}$ is the maximum of critical temperature obtained for the OP sample, $T_{c,\,\mathrm{max}} = 96\,\mathrm{K}$. In turn, the T_c values are determined from the susceptibility-versus-temperature measurements. The results of the AC-susceptibility measurements for three samples (OD, OP, UD1) are shown in Fig. 1. The temperature of the diamagnetic response appearance was taken as T_c. Above this temperature the susceptibility is close to zero. Below T_c the sample diamagnetism due to the Meissner shielding currents results in the negative in-phase signal proportional to a susceptibility.

The temperature dependence of the MWA amplitude for three samples with different concentrations of charge carriers (OD, OP, UD1) is shown in Fig. 2. The dependence has the simplest shape for the OD sample: the amplitude of the MWA signal decreases slightly in the area $T > T_c$ and falls abruptly at T_c. Such behavior is easy to understand if one considers that MWA being due to energy dissipation upon flowing eddy currents induced by microwave field. In the normal state these currents flow in the skin layer. The skin layer depth δ is determined by the material resistivity ρ through the equation $\delta = \sqrt{2\rho/\omega\mu}$, ω is a microwave frequency and μ is magnetic permeability of a sample. Therefore, the MWA value also has the root dependence on resistivity, $A_{\mathrm{MWA}} \sim \sqrt{\rho}$.

Upon the transition to superconducting state the current carriers form Cooper pairs. Since they are not scattered on the lattice and defects, the MWA magnitude reduces abruptly. However, it does not vanish. Here its value is determined by the energy dissipation upon a vortex motion. And the skin depth is determined by the depth of penetration of the magnetic field into the superconductor [6].

In the cases of optimally doped and underdoped samples the MWA amplitude changes with the temperature decrease in the similar way. There is only one but significant distinction: the presence of the MWA peak close to T_c (above it). This effect cannot be explained with the resistivity variation only. It is necessary to explore the 2D character of studied material and the superconducting fluctuation appearance near the critical temperature. Such explanation had been proposed in the paper [7]. It is as follows. Owing to the quasi-two-dimensional structure

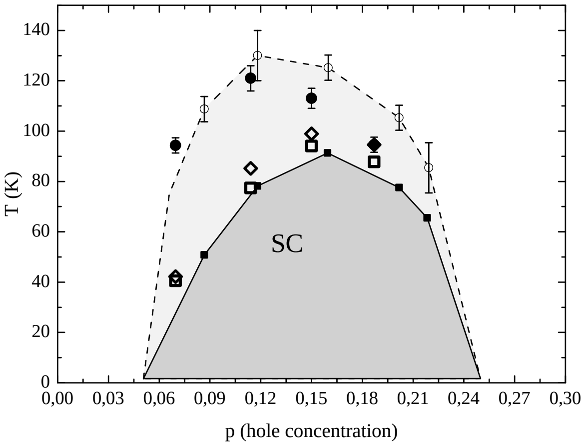

Figure 3. Points of the superconducting phase region (dark gray) border $T_c(p)$ are obtained with the AC-susceptibility measurements (□ – this work, ■ – Ref. [2]) and with MWA measurements (◇). The fluctuation region (light gray) border is shown by black circles (MWA, this work) and by white circles (Nernst effect [2]).

of samples the resistance in the *ab* planes behaves as a metal resistance and in the perpendicular direction the resistance has the semiconductor character, and it is four orders of magnitude larger than in plane. With decreasing the temperature to the superconducting transition from above the superconducting fluctuations appear. They have a two-dimensional character as well, and this leads to the increase of conductivity in CuO_2 planes. At the same time, the density of normal (unpaired) carriers decreases. Since just these carriers determine the resistivity in the direction perpendicular to the CuO_2 layers, it grows. As a consequence, the skin depth increases together with MWA. Thus superconducting fluctuations manifest themselves in the form of the MWA peak near the critical temperature [7]. The temperature point, where the A_{MWA} deviates from linear dependence, we define as the border point of the fluctuation area (as seen by MWA measurement). Having such data for four samples with the hole density varying in the wide range we can plot the upper fluctuation area border $T_f(p)$ on the phase diagram $T_i(p)$ (see Fig. 3). Its lower border is determined as the critical temperature dependence $T_c(p)$ from the AC susceptibility data.

In the phase diagram (Fig. 3) our data are presented together with that of Ref. [2] where the fluctuation area was obtained from the Nernst effect measurements. It is shown as light gray region. The dark gray region corresponds to the superconducting phase. The superconducting transition temperatures obtained from our AC-susceptibility measurements are shown by white squares. It is seen that our points $T_c(p)$ lie slightly higher than that of data [2] (black squares). It is characteristic for the Bi2212 samples with the yttrium impurity [8]. As for the upper border of the fluctuation region, there is some divergence of data obtained by two methods for the optimally doped and overdoped samples, while the data for underdoped samples agree well (see Fig. 3). However, our MWA measurements reflect better the trend found with the STM study [2], namely, the constriction of the temperature range with the gaped state upon the hole density increase.

It should be noted that the superconducting fluctuations manifest themselves evidently in the MWA measurements. So one can assume that their lifetimes exceed period of microwave oscillations in this temperature range (from T_c to T_f). This allows us to conclude that the fluctuation lifetime is no less that 10^{-10} s.

Thus, in present work using AC-susceptibility and MVA measurements we determined the boundaries of area of the superconducting order parameter fluctuations. Moreover, the estimation of the fluctuation lifetime is made.

Acknowledgments

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