Pis'ma v ZhETF, vol. 108, iss. 10, pp. 704 – 705

Microwave absorption by charge density waves in $La_{2-x}Sr_xCuO_4$

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Submitted 21 September 2018
Resubmitted 12 October 2018

DOI: 10.1134/S0370274X1822006X

The idea of electronic phase separation in the form of charge stripes or charge density waves (CDWs) in cuprate superconductors was proposed at the very beginning of the high-temperature superconductivity era [1, 2]. They had been detected by neutron studies of compounds $La_{2-x}Ba_xCuO_4$ and $La_{2-x}Sr_xNd_{0.4}CuO_4$ with x close to 0.125, where stripes are static and easily detected [3]. In other cases, charge stripes are not observed directly owing to their high mobility. The measurements of the Seebeck coefficient in strong magnetic fields led the authors of [4] to the conclusion that the strontium concentration range of the CDW existence is limited by values from 0.085 to 1.50. However, they manifested themselves in the transport properties of $La_{2-x}Sr_xCuO_4$ (LSCO) with very small x, down to 0.01 [5]. The contradiction between these data obtained by two different methods motivated us to study the transport properties of LSCO ($x = 0.077 \div 0.195$) using the direct current (DC) resistivity measurements and the microwave absorption (MWA). The MWA is determined by ohmic loss, and it is convenient to compare it with the resistivity data. At the same time, the high frequency of the measurement ($\sim 10^{10}$ Hz) makes it sensitive to the short-lived and dynamical objects like CDWs in LSCO crystals.

We studied $La_{2-x}Sr_xCuO_4$ single crystals grown using the traveling solvent floating zone techniques at the Tohoku University, Japan. The detailed description of the crystal preparation procedure is given in [6]. The crystal set at our disposal covers a range from highly underdoped (UD) samples ($x = 0.077$) through optimally doped (OP) ones ($x = 0.16$) to overdoped (OD) crystals with $x = 0.195$.

The AC susceptibility versus temperature measurements were used to determine the superconducting transition temperature T_c. The measurements were carried at the frequency of 1.38 kHz in the magnetic field $H_a = 25$ Oe applied perpendicular to the ab crystal plane. The T_c values determined from the magnetic AC-susceptibility measurements in our work coincide very closely with the data of [7].

An electron spin resonance spectrometer was used as the high-frequency instrument sensitive to the weak short-lived electron excitations. The BER-418s spectrometer (Bruker) operates at the frequency of $\sim 9.3 \cdot 10^9$ Hz with the modulation of 100 kHz. For the comparative analysis, we measured the direct current resistance using a standard four-probe method.

According to the experimental study and the theoretical calculations (see, for example [8]) the resistivity of LSCO crystals above the critical temperature T_c has to be linear function for the underdoped samples and it is quadratic for the optimally doped and overdoped ones. The deviation from such dependence could arise in the form of a cusp (the change of the slope sign) when the additional scattering channel (such as CDWs) appears. Nevertheless, this effect cannot be detected with the DC resistance measurements due to high CDW mobility. However, it is revealed via the MWA measurements performed at high frequency $9.3 \cdot 10^9$ Hz. The comparison of the MWA signal amplitude $A_{\rm mwa}$ versus temperature with $R(T)$ is shown in Fig. 1 for one of UD samples as an example. One can see the deviation from the linear function $A_{\rm mwa}(T)$ in the temperature range from $T \sim 55$ K down to the superconducting transition. The same deviation is observed for all underdoped samples but it is absent in OP and OD samples.

It is known that the superconducting fluctuations (SCFs) contribute to MWA at temperatures close to T_c as well [9]. In order to separate these two contributions (CDW and SCF), we studied the effect of the magnetic field on the MWA amplitude versus temperature. The MWA loss peak due to SCFs becomes broadened and shifted with increasing field while the CDW con-

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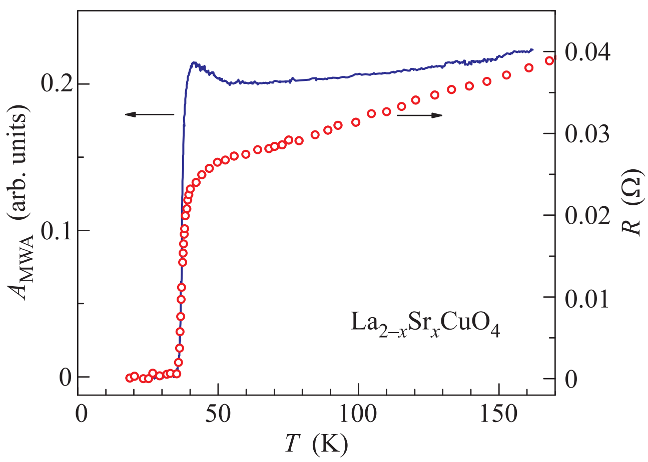

Fig. 1. (Color online) Temperature dependence of the resistance (points) and the MWA signal amplitude (line) for the UD sample with $x = 0.142$

tribution is unaffected by magnetic field. Thus, tracing the course of the $A_{\rm mwa}(T)$ curve at various magnetic fields we obtained the boundary points of the regions with CDWs, superconducting fluctuations and the bulk superconductivity state, and plot them on the doping-temperature phase diagram of the $La_{2-x}Sr_xCuO_4$ compound together with the literature data taken from other method measurements for comparison.

The SCF boundary points obtained in our study are located slightly below the corresponding points measured using the terahertz spectroscopy [10]. It is easily understood taking into account that the measurements at higher frequency ($\sim 10^{12}$ Hz in [10] instead of $\sim 10^{10}$ Hz in our study) make it possible to detect fluctuations with shorter lifetime existing at higher temperatures. The discrepancy of the $T_{\rm CDW}(x)$ values obtained from MWA measurements and the X-Ray Diffraction (XRD) study [11] is more remarkable. Our data demonstrate that the region of the CDW existence is broader over the hole density x. CDWs are manifested in all UD samples from $x = 0.077$ upto 0.142. The upper value agrees well with the limit determined by the measurements of the Seebeck coefficient in high magnetic fields [4]. The authors of [4] have concluded that the CDW phase in LSCO ends at the critical doping $x = 0.15$. However, they have established the lower boundary at $x = 0.085$. But in our study CDWs are observed down to $x = 0.077$, that is noticeably lower. Thus, our data contradict to those of [4]. But they agree better with the transport study data [5], which imply the CDW presence down to the very low hole density, $x \approx 0.01$.

I.I.G. was supported by the Russian Academy of Sciences in the framework of Program 1.12 “Fundamental problems of high-temperature superconductivity”.

Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S0021364018220034

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