JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 8, No. 3, June 2006, p. 1072 - 1076

Short-wavelength fluctuation regime in paraconductivity of bulk monophase (Bi, Pb)-2223 superconductor system

A. HARABOR[*], N. A. HARABOR[a], M. DELETTER[b]
Faculty of Physics, University of Craiova, 13 A. I. Cuza Str., Craiova-200585, Romania
[a] „Politehnica" University, Bucharest, Romania
[b] Centre de Recherche de la Céramique, Mons, Belgium

The Aslamasov-Larkin contribution of the excess-conductivity, calculated within the Lorentz-Doniach model shows that a crossover from 3D to 2D dimensionality is taken place at about 110.41K for our bulk monophase (Bi, Pb)-2223 samples. A bending of the log-log curves from 2D behavior through those of SWF (short wavelength fluctuation) behavior was also observed at a temperature about 135.43K (far from T_{cm}). The theoretical fits are also consistent with the following formula for paraconductivity ($\Delta\sigma=(e^2/16\ \hbar s)f(\varepsilon)$) expressed in terms of so called universal function $f(\varepsilon)$, where $\varepsilon = \ln(T/T_c)$. In the Ginzburg-Landau region ($\varepsilon << 1$) we take $f(\varepsilon) = 1/\varepsilon$, but in the SWF region ($\varepsilon >> 1$) we have $f(\varepsilon)=1/\varepsilon^3$.

(Received March 15, 2006; accepted May 18, 2006)

Keywords: Superconductivity, Paraconductivity, (Bi, Pb)2223 system

1. Introduction

Owing to the strong anisotropy, high critical temperatures, and small coherence length the high temperature superconductors (HTSC) show in zero magnetic field a pronounced effect of thermodynamic fluctuations above the superconducting transition temperature. The theory of Aslamazov-Larkin (AL) of noninteracting, Gaussian fluctuations [1] has been successfully used to explain the enhancement of conductivity (denoted Para conductivity), due to the presence of thermal fluctuations of Cooper pairs above Tic, in zero magnetic field and for small electric fields.

Lawrence and Doniach [2] have extended the initial Aslamasov-Larkin expression of paraconductivity for the two-dimensional layered superconductors. The HTSC are strongly anisotropic layered materials and the study of paraconductivity in the framework of Lawrence-Doniach (LD) model evidenced in the vicinity of T_c a crossover between three-dimensional and two-dimensional regimes in the majority of HTSC compounds.

The LD crossover can be shown explicitly in the framework of Gauss-Ginzburg-Landau (GGL) theory for an isotropic spectrum, when the fluctuation contribution to the free energy of a superconductor, just above T_c, can be presented as the sum over long-wavelength fluctuations [3]. It is essential to note that the GGL approach should be correct in the range where the reduced temperature ε, is supposed to be small, ($\varepsilon << 1$).

One of the problems still open at present is the behavior of the thermodynamic fluctuations far from transition in the high-reduced temperature region ($\varepsilon \geq 0.1$), when a break down of the GGL approach in the description of fluctuations is reported. We have a crossover the so-called short-wavelength fluctuations (SWF) effects that appear when their characteristic wavelength became of the order of coherence length $\xi(0)$.

These called short-wavelength fluctuations break down the „slow variation condition" for the superconducting order parameter, the central hypothesis of the GGL approach. It was shown that the GGL approaches could be extended to the SWF region by introducing a momentum cutoff ($k^2 < c\xi^{-2}(0)$) in the fluctuation spectrum ([4], [5], [6]) or a cutoff in the total energy ($\left[k^2 + \xi^{-2}(\varepsilon)\right] < c\xi^{-2}(0)$) of the fluctuation modes (in units of $\hbar^2/2m^*$, where m* is the effective mass of the Cooper pairs, k is the momentum of each fluctuating mode, c is constant cutoff amplitude close to 1). The last condition [7] eliminates the most energetic fluctuating modes and not only those with short wavelength. The author of [7] calculated the in plane $\Delta\sigma$ under the both conditions.

For the 2D non-cutoff limit of paraconductivity, one should have $f(\varepsilon) = 1/\varepsilon$ (by imposing the condition $\varepsilon << c$ in the expressions under momentum or energy cutoff). This result coincides with the well-known 2D contribution from Aslamazov-Larkin theory. For clean two-dimensional superconductors, in no-cutoff limit SWF region, where $\varepsilon \geq 0.1$, it was found that $f(\varepsilon) = 1/\varepsilon^3$. This was obtained by imposing the condition $\varepsilon >> c$ in the expressions under momentum cutoff or under energy cutoff. The similar conclusions were obtained in ref. [8] within the self-consistent Hartree approximation.

In this generalized form the two-dimensional paraconductivity is universal. Because it contains only an intrinsic parameter s as a prefactor, it permits us to rescale the results and to compare them for different compounds.

In our paper we present the paraconductivity results expressed in terms of the universal function f(ε) for a monophase bulk (Bi, Pb)-2223 sample and we will show that we have a good fit within the 2D and SWF no-cutoff limit of paraconductivity as predicted by Aslamazov-Larkin theory of and Lawrence-Doniach model.

2. Some theoretical considerations on paraconductivity

The Aslamazov-Larkin theory provide the following expression for the excess-conductivity above T_c generated by the thermodynamic fluctuations:

$$\frac{\Delta\sigma}{\sigma_0} = A\varepsilon^{\lambda} \tag{1}$$

Here $\Delta\sigma$ is defined by

$$\Delta\sigma = \sigma_m - \sigma_n \tag{2}$$

$\sigma_m(T)$ is the measured conductivity and $\sigma_n(T)$ is the extrapolated conductivity under the assumption of a linear or a Zou-Anderson dependence for resistivity $\rho(T) = \frac{1}{\sigma(T)}$ above $2T_c$; $\sigma_0 = \frac{1}{\rho_r}$ is the conductivity calculated from the room temperature resistivity (ρ_r) measured at T=300 K and ε is the reduced temperature

$$\varepsilon = \ln\frac{T}{T_c} \tag{3}$$

In the limit of GGL approach, $\varepsilon << 1$ and we have the following approximation for the reduced temperature, often used in the Aslamazov-Larkin theory

$$\varepsilon = \ln(T/T_C) \cong \frac{T - T_c}{T_c} \tag{4}$$

Here $T_c = T_{cm}$ (T_{cm} being the mean field critical temperature);
λ is a parameter depending on dimensionality, with two contributions:

a) 3D contribution for λ=-0.5 and $A=A_{3D}$, when we can write:

$$\frac{\Delta\sigma}{\sigma_0} = A_{3D}\varepsilon^{-0.5} \text{ with } A_{3D} = \frac{e^2\rho_r}{32\hbar\xi(0)} \tag{5}$$

$\xi(0)$ is the zero-temperature coherence length in the stacking direction of multilayer structure.

b) 2D contribution for λ=-1 and $A=A_{2D}$, when the excess-conductivity is written as:

$$\frac{\Delta\sigma}{\sigma_0} = A_{2D}\varepsilon^{-1} \text{ with } A_{2D} = \frac{e^2\rho_r}{16\hbar d} \tag{6}$$

where d is the superconducting layers periodicity length.

The analysis of the excess conductivity above the mean critical transition temperature T_{cm} (taken as T_c) were performed in the framework of the Lawrence-Doniach model [2], suited for layered superconductors. In this model the excess conductivity takes place in the superconducting layers coupled by Josephson tunneling

$$\frac{\Delta\sigma}{\sigma_0} = A\varepsilon^{-0.5}(\varepsilon + 4J) \text{ with } A = \frac{e^2}{16d\hbar\sigma_0} \text{ and } J = \left(\frac{\xi(0)}{d}\right)^2 \tag{8}$$

J is the constant coupling between the superconducting layers and A is the temperature-independent amplitude, $\xi(0)$ is the coherence length in the stacking direction of the multilayer structure at T=0 and d is the interlayer spacing. For the weak coupling $4J << 1$ the eq. (8) reduces to the 2D term. The 3D term is obtained in the condition 4J>>1.

Therefore it results the following expression for the crossover temperature, T_{cr}, between 2D and 3D dimensionality:

$$T_{cr} = T_{cm}\left[1 + 4\left(\frac{\xi(0)}{d}\right)^2\right] \tag{9}$$

All the terms described above are included in the appropriate generalization of the Aslamazov-Larkin expression of paraconductivity discussed in the introduction [3]:

$$\Delta\sigma = \frac{e^2}{16\hbar s} f(\varepsilon) \tag{10}$$

f(ε) is the so-called universal function that should take the following forms, depending of the reduced temperature, ε:

1) for $\varepsilon << 1$ we are within the GGL of 2D paraconductivity described by Aslamazov-Larkin theory:

$$f(\varepsilon) = \frac{1}{\varepsilon} \tag{11}$$

2) For $\varepsilon \geq 0.1$, the short wavelength fluctuations (SWF) appear when their characteristic wavelength became of the order of coherence length, $\xi(0)$. Within SWF region in the limit of non- cutoff theory one should have:

$$f(\varepsilon) = \frac{1}{\varepsilon^3} \tag{12}$$

3. Experimental results and discussion

3.1 X-Ray diffraction analysis

It is well known that the synthesis of single-phase Bi-2223 samples is quite difficult. By using both Cu-rich starting compositions and a material co-doped with small amount of Pb in Bi-Sr-Ca-Cu-O system, we obtained bulk (Bi, Pb)-2223 single phase samples, the preparation procedure being reported in ref. [9].

The microstructure of the sample was investigated by XRD analysis performed on a PHILIPS PW 1710 equipment with CuK_α radiation. The Bragg diffraction patterns are presented in Fig. 1. The unit cell of (Bi, Pb)-2223 material was indexed as tetragonal structure with the following lattice constants: $a \cong b = 5.39$ Å and c=37.05 Å.

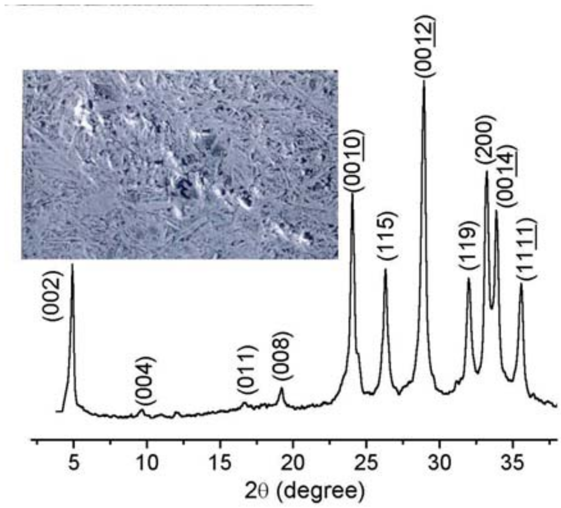

Fig. 1. X-ray diffraction patterns for single-phase (Bi, Pb)-2223 samples. In the inset is given a SEM-EDX image obtained with a JEOL T type microscope (x1000 times).

It is known that in the half of unit cell of 2223 phase we have two Cu-O pyramids (five coordination's in CuO_2 planes outside the two Ca layers) and one additional Cu-O sheet (four coordination's in CuO_2 plane between the two Ca layers). Our calculated values for lattice parameters are similar with those communicated by Natsume et al. [10].

The SEM-EDX analysis was made with a JEOL T type microscope. The image presented in the inset of Fig. 1 is the prove that the sample has o good homogeneity. It is to note that even if the diffraction peaks exhibited a single-phase compound, a very small fraction of impurities are still present, which appear as black crystals dispersed on the sample surface.

3.2 Resistivity and paraconductivity

Four-probe DC resistivity data of rectangular slab samples were acquired in the temperature range of 20 K to 293 K at different magnetic fields in the range 0 to 0.7 T and at a current density of 0.7 A/cm^2. Conductive silver paste was used to attach the gold leads to the specimens. High-resolution electrical resistivity data have been taken using a Keithley 220 programmable current source, a Keithley 181 nanovoltmeter, and a Keithley 182 sensitive digital voltmeter, a Lakeshore temperature controller and a closed-cycle helium refrigerator.

Two methods may be used in order to estimate the resistivity versus temperature in the normal state: one is Zou-Anderson method, which predict a $\rho = AT + (B/T)$ fit function; the other is the linear dependence for resistivity $\rho(T)$. The plot of the resistivity versus temperature exhibits two different regimes. The one is corresponding to the normal state that shows a metallic behavior (above $2T_{cm}$) emphasized by a linear fit relations:

The other is the region characterized by the contribution of induced fluctuation Cooper pairs to the conductivity (the AL term) above T_c, where $\rho(T)$ is deviating from linearity.

An additional contribution may be the Maki-Thomson term that is associated with the increase in the normal electron conductivity induced by superconducting fluctuations. In cleaner films the MT term gains importance.

The above considerations are illustrated in the examples given in Fig. 2.

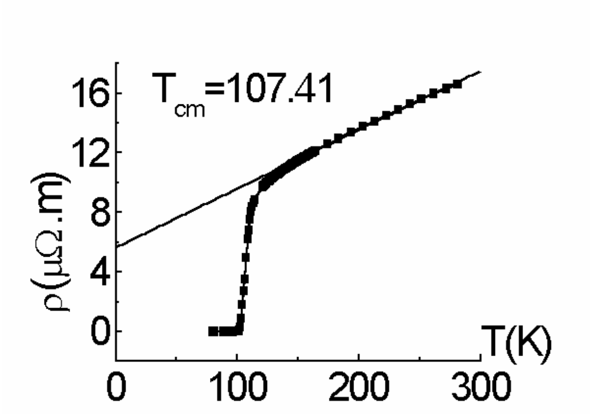

Fig. 2. The measured resistivity. The solid line is the extrapolated resistivity in the assumption of a linear dependence versus temperature above $2T_c$.

The linear fit for the experimental $\rho(T)$ (solid line) above $2T_c$ is deduced by regression analysis. In our study the transition temperature T_c was estimated as the so-called mean field critical temperature T_{cm} as being equal with the temperature of the main peak in the $d\rho/dT$ versus T plots.

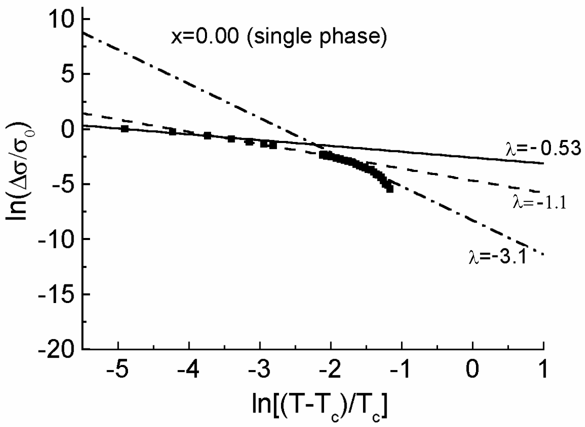

Fig. 3. The log-log plots for the paraconductivity of single (Bi, Pb)-2223 phase in the framework of Larkin-Aslamazov theory. The solid lines show the theoretical approaches.

From the experimental $\ln\frac{\sigma}{\sigma_0}$ versus $\ln\left(\frac{T-T_c}{T_c}\right)$ (the log-log plots) given in Fig. 3, we have obtained through a regression analysis the values of the parameter λ as the slope of the curve) in order to verify the theoretical predictions presented above. The λ parameter gives us information about the dimensionality of the order parameter fluctuations for the superconducting system. Two straight lines are clearly present in the log-log plots (shown in Fig. 3), with the slopes of λ equals -0.5 (the 3D dimensionality near T_{cm}) and of λ=-1 (2D dimensionality) respectively. There is also a bending to the so-called SWF (short wavelength fluctuation) behavior, where λ=-3.

The log-log plots facilitate also the estimation of cross-over temperature T_{cr} from 2D to 3D dimensionality and then the possibility to calculate the coherence length $\xi(0)$ at 0 K (by substitution of T_{cr} from 3D to 2D, experimentally determined, in the Eq. 9), the estimation of the cross-over temperature T* from 2D to SWF behavior and of $\varepsilon^* = \ln\frac{T^*}{T}$.

When we are doing all this calculations we have to pay attention to the fact that all these parameters are depending on the interval of temperature in which the linear ρ(T) was appreciated, in order to evaluate the paraconductive behavior. To illustrate this we have chosen five different intervals for the linear ρ(T) dependence.

Table 1.

Interval (K)	Linear ρ(T) dependence ($\mu\Omega$.m)
212.72÷281.39	6.4624+0.03622 T
193.52÷281.39	6.2098+0.03721 T
173.94÷281.39	6.0400+0.03788 T
164.106÷281.39	5.9415+0.03828 T
163.12÷281.39	5.8627+0.03861 T

In the Table 2 are given the values of the parameters corresponding to the five arbitrary chosen intervals.

Table 2.

Interval (K)	λ_{3D}	λ_{2D}	λ_{SWF}	T_{cr}^{2D-3D} (K)	$\xi(0)$ (Å)	T* (K)	ε^*
212.72÷281.39	-0.54 err.7.18%	-1.043 (err err.1.65%)	-3.00 err.12.72	113.206	4.3	146.64	0.311
193.52÷281.39	-0.557 err.7.49%	-1.004 err.1.96%	-2.995 err.15.12%	111.59	3.65	142.535	0.283
173.94÷281.39	-0.567 err.7.71%	-0.993 err.1.69%	-2.959 err.17.38%	110.848	3.31	139.27	0.259
164.106÷281.39	-0.573 err.7.85%	-1.030 err.1.9%	-3.009 err.7.29%	110.922	3.34	137.54	0.247
163.12÷281.39	-0.578 err.7.95%	-1.005 err.1.29%	-3.025 err.9.45%	110.656	3.22	135.016	0.228

As observed from the Table 2 the error in evaluated λ is smallest for the 2D region and higher or the 3D and SWF regions. Another observation is that T_{cr}^{2D-3D} and the crossover temperature T* from 2D to SWF behavior (as well as the corresponding reduced temperature ε^*) decrease with the decrease of the lower temperature value of the temperature interval. One can also remark that the coherence length in the c-direction is less than the dimensions of the unit cell.

Cimberle et al. [3] has analyzed the applicability of so called universal function f(ε) from the formula give in eq. (10) that is considered as a generalization of the Aslamazov-Larkin theory of paraconductivity available also in the range of temperatures above and far away from $T_{cm.}$ Accordingly with those formula for $\varepsilon << 1$ (the GL region of temperatures) the result should be in good agreement with Aslamazov-Larkin one $f(\varepsilon) = 1/\varepsilon$. But for $\varepsilon \geq 0.1$ it was found the following dependence: $f(\varepsilon) = 1/\varepsilon^3$ known as the called SWF (short wavelength fluctuation) behavior.

The authors of the paper mentioned above have verified their theoretical predictions for three samples and found that for all the investigated samples (Bi-2212 sample, Bi-2223 sample and YBCO-123 sample) the crossover from the two dimensional paraconductivity to the asymptotic (SWF) behavior takes places universally at $\varepsilon^* \cong 0.23$.

The analysis of our results shows that there is an evident bending of the log-log curves from 2D through those of SWF (short wavelength fluctuation) behavior with λ=-3 for our pure 2223-samples. However the crossover point from 2D to SWF behavior is strongly dependent of the interval chosen for appreciate the linear dependence of resistivity as seen in the Table 2.

4. Conclusions

The 3D, 2D and SWF behaviors have been observed in a single phase (Bi, Pb)-2223 sample with the best fit in the framework of non-cutoff limit of paraconductivity (as well as in the Aslamazov-Larkin theory and Lorentz-Doniach model). The coherence length is smaller than the lattice constants and the crossover temperatures from 3D-2D and from 2D to SWF are strongly dependent on the interval in which is appreciated the linear dependence of resistivity versus temperature. This is in contradiction with the Cimberle results [3], who found for three different samples the same value of 0.23 for the crossover reduced temperature from 2D to SWF.

Acknowledgment

This work was partially supported by Belgium Government. We are grateful to J. Dutrieux from Mons University for doing SEM and EDX measurements.

References

[1] L. G. Aslamazov, A. I. Larkin, Phys. Lett. **26A**, 238 (1968).
[2] W. E. Lawrence, S. Doniach, 1970 Proc. 12th. Int. Conf. Low. Temp. Phys., Kyoto Japan, 261-2, edited by A Kanda (Keygaku, Tokyo, 1970).
[3] M. R. Cimberle, C. Ferdeghini, E. Geannini, D. Marre, M. Putti, A. Siri, Phys. Rev. B **55**(22), R14745-R14747 (1997).
[4] Johnson and Tsuei, Phys. Rev. B **13**, 4827 (1976).
[5] A. P. Levanyuk, Fiz. Tverd. Tela **5**, 1776 (1963).
[6] A. Schmid, Phys. Rev. B **180**, 527 (1969).
[7] C. Carballeira, S. Curras, J. Vina, J. Veira, Phys. Rev. B **63**, 144515 (2001).
[8] I. Puica, W. Lang, cond-mat/0306574, v1 (2003).
[9] A. Harabor, A. V. Pop, R. Deltour, J. Schroeder, D. Ciurchea, Gh. Ilonca, Journal of Low Temperature Physics **105**, 1053 (1996).
[10] H. Natsume, T. Kishimoto, H. Enomoto, J. H. Shin, Y. Takano, N. Mori, H. Ozaki, Jpn. J. Appl. Phys. **30**, L461 (1991).

*Corresponding author: harabor@central.ucv.ro