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Thermal Fluctuations of $(Tl_{0.5}Pb_{0.5})Sr_2(Ca_{0.9}Gd_{0.1})Cu_2O_z$ Bulk Superconductor

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We report on the critical fluctuations from the magnetoresistance measurements in polycrystalline $(Tl_{0.5}Pb_{0.5})Sr_2(Ca_{0.9}Gd_{0.1})Cu_2O_z$ superconductor. The critical exponents have been calculated above the critical temperature T_c as well as in the temperatures interval close to the zero resistance critical temperature. Above T_c only Gaussian fluctuations have been observed in a three-dimensional fluctuating system. Additionally, far above T_c the applied magnetic field induces the crossover from 3D to 2D fluctuating system. At the temperatures range close to the zero critical temperature the properties of the weak links are dominating and the fluctuating phase in each grain becomes long-range ordered as a consequence of the activation of weak links between grains.

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1. Introduction

The very short coherence length as well as the large anisotropy of high temperature superconductors (HTS) affect on the thermal fluctuations around the superconducting transition. Within the critical region one can notice the competition between the critical fluctuations at lower temperatures and the Gaussian (stochastic) fluctuations at the temperatures far above the critical temperatures that depend on the applied magnetic field as well as the applied pressure [1–3]. The Gaussian fluctuations can give the information on the effective dimensionality of superconductivity in HTS materials. The thallium based superconductors are very rewarding subjects of these studies because of their special behavior of widening of the resistive transitions upon the influence of the applied magnetic field. Because of huge anisotropy the superconductors have generally the three-dimensional (3D) to the two-dimensional (2D) transition in the critical region for polycrystalline, single crystal as well as for thin film samples [4–7].

In this paper we report on the magnetic field dependent thermal fluctuations in the $(Tl_{0.5}Pb_{0.5})Sr_2(Ca_{0.9}Gd_{0.1})Cu_2O_z$ bulk superconductor. As it was shown in the paper [8] the superconducting properties of these kind of thallium superconductors are very interesting and they strongly depend on the gadolinium content.

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2. Experiment

The sample was prepared by the sol–gel method according to the procedure described in detail in the paper [9]. The measurements of the resistance versus temperature for different values of the applied dc magnetic fields were carried out using the four-point ac method of 7 Hz current frequency using Stanford SR 830 lock-in nanovoltmeter. The applied dc magnetic field was produced by a copper solenoid immersed in a liquid nitrogen bath. The temperature from 77 K to 170 K was monitored by a Lake Shore temperature controller employing a chromel–gold–0.07% Fe thermocouple with an accuracy of ±0.05 K. The electrical contacts were made by silver paint which were sintered at 300 °C.

The critical temperatures of this sample are as follows: $T_{c50\%} = 101.1$ K, $T_{c0} = 94.9$ K and the onset temperature $T_{c,onset} = 105.7$ K. The transition was of width $\Delta T_{90\%–10\%} = 5.6$ K without applied magnetic field.

3. Results and discussion

The temperature dependences of the resistance were done for several values of the applied dc magnetic fields. To analyze them the field dependent conductivity within the transition region was used in the following form [10]:

$$\Delta\sigma = K\varepsilon^{-\lambda}, \quad (1)$$

where $\varepsilon = \frac{T-T_c}{T_c}$, λ is the critical exponent, K is a constant. The temperature dependence of excess conductivity is defined within the Ginzburg–Landau mean field approximation [11]:

$$\Delta\sigma(T) = \frac{1}{R(T)} - \frac{1}{R_{\rm R}(T)}, \tag{2}$$

where $R(T)$ is the measured resistivity and $R_{\rm R}(T)$ is the resistivity obtained by the linear extrapolation of resistivity data from about 170 K down to the onset temperature [12].

Assuming that the resistivity $R(T)$ follows a linear temperature dependence at higher temperatures, it is obtained by linear fitting of resistivity curve and extrapolating the same to below $T_{\rm c}$. The determination of $\Delta\sigma$ involved the determination of $R_{\rm R}$ for temperatures near $T_{\rm c}$ by extrapolating the high temperature behavior of $R_{\rm R}(T)$ as follows:

$$R_{\rm R}(T) = R_0 + \left(\frac{{\rm d}R}{{\rm d}T}\right)T, \tag{3}$$

where R_0 and ${\rm d}R/{\rm d}T$ are constants.

The linearity of $R_{\rm R}(T)$ is observed in all measurements above 130 K.

In the critical region, in which the critical fluctuations are observed the full dynamical scaling theory [13] predicts that the excess conductivity (Eq. (1)) diverges at the critical temperature with the critical exponent given by the relation

$$\lambda = \nu(2 + z - d + \eta), \tag{4}$$

where ν is the critical exponent for the coherence length, z is the dynamical exponent, d is the dimensionality of fluctuation spectrum and η is exponent for the order parameter of the correlation function. The thermodynamic properties of superconductors in the critical region are the same as for 3D-XY model. Then one should substitute $\nu = 2/3$, $z \approx 3/2$ and $\eta = 0$.

In the regimes further from the critical temperature the critical exponents are dominated by Gaussian fluctuations. The mean field Ginzburg–Landau theory predicts that $\nu = 1/3$, $z = 2$ and $\eta = 0$. Thus as shown by Aslamasov and Larkin [10], the Gaussian fluctuations can be described by

$$\lambda = 2 - \frac{d}{2}, \tag{5}$$

where d is the dimensionality of fluctuation spectrum.

To determine the critical exponents we plotted the temperature dependence of the following expression:

$$-\left[\frac{\rm d}{{\rm d}T}\ln\left(\frac{1}{R} - \frac{1}{R_{\rm R}}\right)\right]^{-1} = \frac{1}{\lambda}(T - T_{\rm c}). \tag{6}$$

The critical exponent is a reversal slope of the dependence within a linear regions of the temperature.

The resistance versus temperature for several values of the applied magnetic field is shown in Fig. 1. The temperature derivatives of the resistance near the critical temperature for different values of the applied magnetic field are shown in inset of Fig. 1. The derivatives consist of the two maxima: the first one that is associated with the critical temperature and the second one that is associated with the temperature close to the zero resistance temperature. The second maximum is shifted to

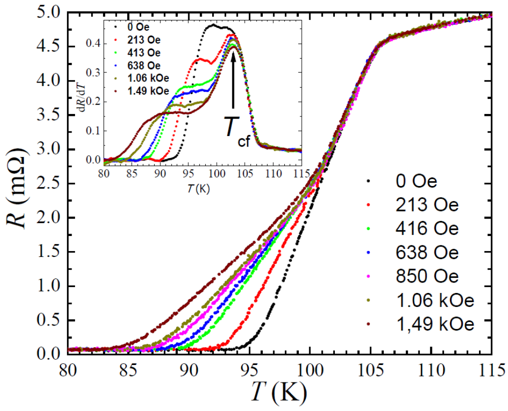

Fig. 1. The resistance versus temperature for several values of the applied magnetic field. Inset: the temperature derivative of the resistivity near the critical temperature for different values of the applied magnetic field.

the lower temperatures if the applied magnetic field increases whereas the first maximum does not depend on the magnetic field up to the maximum fields used in these experiments. The maximum temperature $T_{\rm cf} = 102.8$ K and it is a little bit higher than the critical temperature of this superconductor: $T_{\rm c50\%} = 101.1$ K. Well above $T_{\rm cf}$ the transition is dominated by superconducting fluctuations in the normal state in which the two regions I and II were defined. Two another regions III and IV were defined below the $T_{\rm cf}$ (see Fig. 2), where the temperature fluctuations are dominated by the system of weak links.

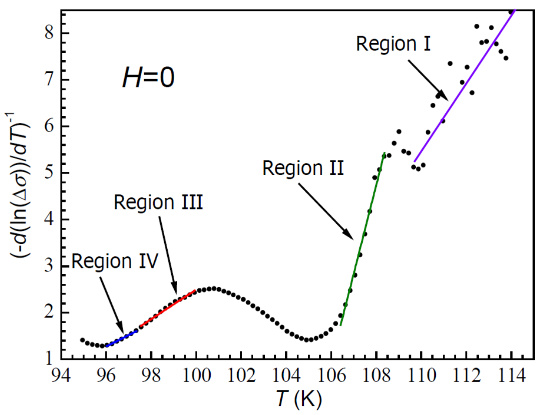

Fig. 2. Representative plot of $(-{\rm d}(\ln(\Delta\sigma))/{\rm d}T)^{-1}$ versus T without applied magnetic fields. There are four regions in which the linear fitting can be obtained (see text).

The critical exponents as a function of the applied magnetic field in the first and second regions were calculated using Eq. (6) and these results are shown in Fig. 3. In the first region the critical exponent is equal to $\lambda = 0.59$ at $H = 0$ Oe. Further on the critical exponents increase with rising of the magnetic field and finally it is $\lambda = 1.0$ at

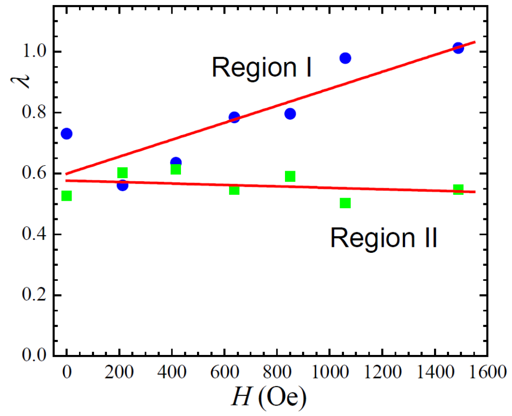

Fig. 3. The calculated critical exponents for region I (closed circles) and for region II (closed squares) with linear fittings.

$H = 1500$ Oe. Using Eq. (5) dimensionalities of the fluctuating system were calculated to be $d = 2.8$ and $d = 2$, respectively. In conclusion one can say that in the region I the applied magnetic field induces the crossover from 3D to 2D fluctuating system. In the region II the critical exponents do not practically depend on the applied magnetic field yielding dimensionality $d = 2.9$ i.e. the 3D fluctuating system. For both regions only Gaussian fluctuations are observed. Also in our previous paper [14] on the shape of specific heat anomaly around T_c in $DyBa_2Cu_3O_x$ we found the large effect of the Gaussian fluctuations within a few Kelvin temperatures interval around T_c. On the contrary for the oriented $(Tl_{0.6}Pb_{0.24}Bi_{0.16})(Ba_{0.1}Sr_{0.9})_2Ca_2Cu_3O_y$ superconducting film on single-crystalline lanthanum aluminate substrate only the critical fluctuations were observed around T_c.

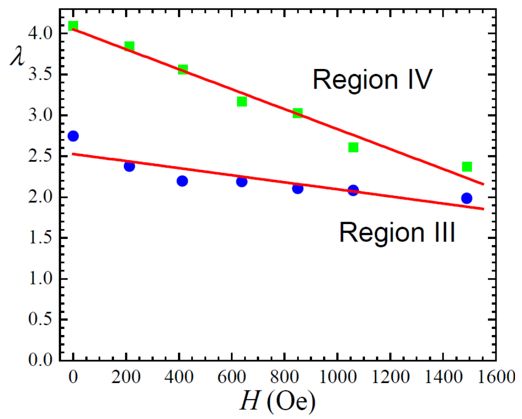

Fig. 4. The calculated critical exponents for region III (closed circles) and for region IV (closed squares) with linear fittings.

In the temperatures range from the zero resistance critical temperature to the $T_{c50\%}$ there are another two regions: III and IV (see Fig. 2). The calculated critical exponents as a function of the applied magnetic field in the third and fourth regions are shown in Fig. 4. In region III the critical exponents are of the order of 2.5 and they weakly decrease when the applied magnetic field increases. In the magnetic field region that was used in this experiment the critical exponent decreases by 24% of its initial value. This region is difficult to be clearly explained. The authors of the paper [1] interpreted this behavior in terms of dissipative flux motion in the presence of the applied magnetic field. On the contrary some authors [15–17] suggest that there is phase transition involving quenched disorder within the system of weak links. They claimed that if the exponents are larger than two (2.2–2.7) [17] the system shows the paracoherent–coherent transitions of the granular array, where the fluctuating phase of the order parameter in each grain becomes long-range ordered as a consequence of the activation of weak links between grains.

In the region IV the critical exponents are of order of 4 and strongly depend on the applied magnetic field. Initial critical exponent is reduced of about 50% at the highest applied field. This phenomenon is difficult to understand. One of the tentative explanation is related to the fluctuations within the inter-grain weak links which strongly depend on the applied magnetic field.

4. Conclusions

The critical exponents of polycrystalline $(Tl_{0.5}Pb_{0.5})Sr_2(Ca_{0.9}Gd_{0.1})Cu_2O_z$ superconductor have been calculated above the critical temperature as well as in the temperatures range close to the zero resistance critical temperature T_{c0}. Above T_c only Gaussian fluctuations have been observed within the three-dimensional (3D) fluctuating system. Far above T_c the applied magnetic field induces the crossover from 3D to 2D fluctuating system. At the temperatures range in the vicinity of the critical temperature T_{c0} the properties of the weak links array play a dominant role in the thermal fluctuations. It means that the critical exponents evaluated for the temperatures below T_c in the region III and IV characterize rather the extrinsic behavior of the sample produced at certain preparation conditions but not the intrinsic physical properties of the superconducting material in general.

Acknowledgments

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