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Coherent transition induced by Sr doping on the $YBa_2Cu_3O_{7-\delta}$ single crystal magnetoconductivity

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Abstract. We have studied by magnetoresistivity measurements the influence of the low Sr chemical doping on the conductivity thermodynamic fluctuation regimes (TFR) of a $YBa_{1.98}Sr_{0.02}Cu_3O_{7-\delta}$ single crystal. The low-current and low-frequency resistivity, $\rho(T,H)$ measurements were performed in a PPMS while DC magnetic fields up to 50kOe were simultaneously applied perpendicular to the ab plane of the single crystal and to the measurement current density. The $d\rho(T,H)/dT$ data shows that the superconducting transition of the sample occur is two stages that corresponds to the signature of a granular superconductor. At this scenario is possible to define two critical temperature transitions $T_C(H)$ and $T_{C0}(H)$ [$T_C(H) > T_{C0}(H)$]. At $T_C(H)$ the superconductivity sets in within the grains and at $T_{C0}(H)$ a coherent transition takes place and a long-range superconducting order takes place over the whole sample. Special attention is reserved to the paracoherent region [$T_{C0}(H) \leq T < T_C(H)$] of the $\rho(T,H)$ data. The field and the temperature dependence of the paracoherent TFR behavior is characterized by a power law represented by a critical exponent $S_0 \approx 3$. This exponent is an indicative that the coherence transition of the sample belongs to the 3D-XY universality class with relevant disorder that probably is associated to the low Sr doping.

1. Introduction

The contribution of the granularity to the superconductor properties of the high temperature superconductors (HTSC) has been an object of the intensity scientific investigation [1,2,3]. In particular AC magnetoresitivity and DC magnetization techniques are successful to characterize its contribution to electrical and magnetic properties of these materials [1,2,3]. The polycrystalline samples prepared by usual solid state reaction techniques are essentially classified as granular superconductors [4,5]. Otherwise the characterization of superconductor single crystals like a granular material is a controversial subject because these are idealized as homogeneous materials [3].

The chemical doping is designated for some works at the literature as an efficient way to introduce an inhomogeneous (granular) character to the superconductor magnetic and electrical properties of $YBa_2Cu_3O_{7-\delta}$ single crystals [1,2,3]. In special magnetic irreversibility studies performed in $Y_{0.98}Ca_{0.02}Ba_2Cu_3O_{7-\delta}$ [3], $YBa_{2-x}Sr_xCu_3O_{7-\delta}$ ($x \leq 0.5$) [2] and $YBa_2Cu_{2.97}Zn_{0.03}O_{7-\delta}$ [1] single crystals show that their irreversible magnetic line dynamics at low magnetic field regime is described by the Almeida-Thouless and the Gabay-Thoulouse power laws that is the magnetic signature of a frustrated and disordered material [2,3]. Otherwise the identification of a magnetoresistivity coherent transition in the electrical property of a superconductor consists in an additional way of characterizes it as a granular material [1,4,5]. As far as we know the report at the literature about magnetoresistivity coherent transition in the HTSC single crystals is scarce [1].

In this work, we report on magnetoresistivity and thermodynamic fluctuation conductivity results of a $YBa_{1.98}Sr_{0.02}Cu_3O_{7-\delta}$ single crystal with the aim of characterizes a granular scenario from the identification of a magnetoconductivity coherent transition.

2. Sample preparation and experimental methods

The single crystals of $YBa_{1.98}Sr_{0.02}Cu_3O_{7-\delta}$ were grown by self-flux method [1] and the selected ones were submitted to an extra oxygen process with the objective of improve their superconducting temperature transition T_C [1]. The single crystal of $YBa_{1.98}Sr_{0.02}Cu_3O_{7-\delta}$ [YB(Sr)CO] used at this work had its structure and superconducting transition characterized respectively by x-ray diffraction (XRD) and electrical resistivity, $\rho(T,H)$. The figure 1(a) displays the XRD result which confirms the $YBa_2Cu_3O_{7-\delta}$ orthorhombic crystalline structure along the c crystallographic axis. The *c* lattice parameter estimate from the figure 1a was $c = (11.67 \pm 0.01)$Å. The superconducting transition of the YB(Sr)CO is highlight in the figure 1(b). The sample presents a sharper transition with $T_C \approx 92{,}6$K. The results presented in the figures 1(a) and 1(b) to the YB(Sr)CO single crystal are in agreement with those reported from literature to samples well oxygenated of this material [6,7].

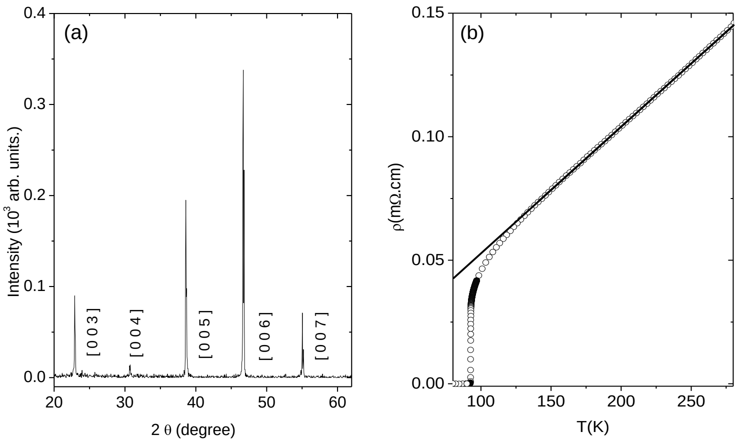

Figure 1. (a) The XRD of the YB(Sr)CO sample obtained for monochromated *CuK α* radiation oriented to its c axis. (b) The $\rho(T,H)$ superconducting transition of the YB(Sr)CO sample.

The four contact $\rho(T,H)$ measurements were performed with AC low current-low frequency PPMS inset while DC magnetic fields up to 50kOe were simultaneously applied parallel to the c axis of the single crystal (H // c) and to the measurement current density (H // J). The $\rho(T,H)$ was recorded while the temperature was decreased from $T > T_C$. During it measurements the temperature was swept very slowly ($\leq$ 0.4 k/min) so that a high number of data points could be recorded in the temperature range of the superconducting transition and the temperature derivative of the resistivity [$d\rho(T)/dT$] could be numerically determinate.

3. Results and Discussion

The upper panels of figures 2 and 3 displays the $\rho(T,H)$ data as well as the lower panels of the figures 2 and 3 displays their correspondent $d\rho(T,H)/dT$ data to $H \leq$ 50kOe applied parallel to

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the c axis. The d$\rho(T,H)$/dT data of the figure 2 shows that the resistive transition of the YB(Sr)CO sample is a single step process. Otherwise The d$\rho(T,H)$/dT data of the figure 3 shows that the resistive transition of the YB(Sr)CO became a two step process to 2.5kOe < $H \leq$ 50kOe. The T_{PAR} is the paring temperature that in $\rho(T,H)$/dT plots corresponds approximately to the T_C. The observation of a two step process to the resistive superconducting transition is a clear manifestation of the granularity. At this scenario the first step corresponds to establishment of the superconductivity within the grains at T_C as well as the second step corresponds to the establishment of a long-range superconducting order over the whole sample resulting in a zero resistivity state. Contrasting the figures 2 and 3 results is reasonable to conclude that the second step resistivity transition could be induced by the magnetic field.

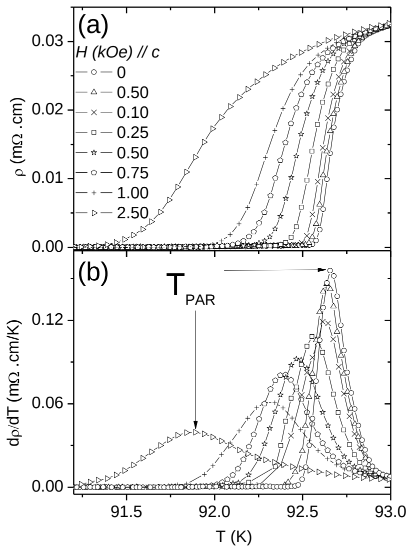

Figure 2. (a) The $\rho(T)$ and (b) the $d\rho(T)/dT$ data to the YB(Sr)CO sample to $H \leq$ 2.5kOe.

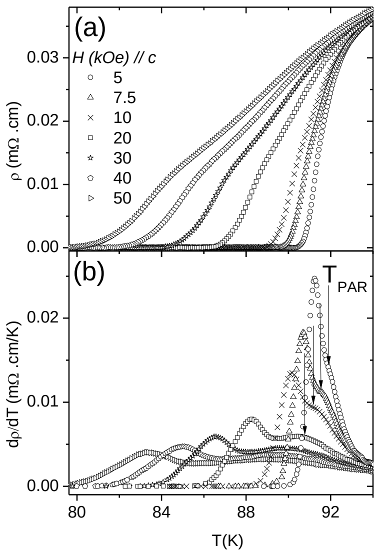

Figure 3. (a) The $\rho(T)$ and (b) the $d\rho(T)/dT$ data to the YB(Sr)CO sample to 5kOe ≤ H ≤ 50kOe.

The contribution of the TFR on the $\rho(T,H)$ data is obtained applying a method based on the Kouvel-Fischer analysis of critical phenomena [8] as highlighted in the figure 4.

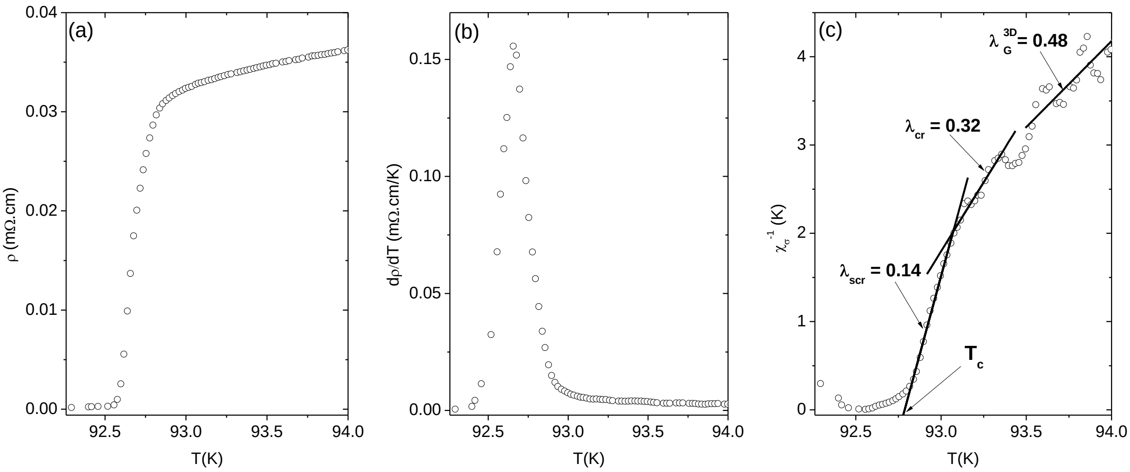

Figure 4. (a) The $\rho(T)$ data, (b) the $d\rho(T)/dT$ data and (c) the$[\chi_\sigma(T)]^{-1}$ data for $H = 0$.

According to this method the TFR on the magnetoconductivity is numerically determined from the quantity:

$$\chi_\sigma = -\frac{d}{dT}[\ln(\Delta\sigma)] \qquad (1)$$

where $\Delta\sigma$ is the fluctuation conductivity extracted from the experimental data as $\Delta\sigma = \sigma - \sigma_R$ where $\sigma = \rho^{-1}$ is the measured conductivity and the subtracted regular term ($\sigma_R = \rho_R^{-1}$) is estimated by extrapolating the high temperature behavior of the $\rho(T)$ data of the figure 1(b).

When the temperature approaches T_C from above we assume that $\Delta\sigma$ diverges as $\Delta\sigma = A(t)^{-\lambda}$ where the reduced temperature is $t = (T - T_C)T_C^{-1}$ and A and λ are the criticals amplitude and exponent, respectively. Then, from equation 1 we obtain

$$\frac{1}{\chi_\sigma} = -\frac{1}{\lambda}(T - T_{c0}) \qquad (2)$$

The existence of asymptotically TFR regimes becomes evident applying the equation (2) in the data of figure 4(c). The extrapolation of the solid line to the temperature axis allows the simultaneously identification of the critical temperature, T_C and the critical TFR λ_{scr}.

The λ_{scr} exponent observed close to the T_C is related to the critical fluctuations. The $[\chi_\sigma(T,H)]^{-1}$ data for $T > T_C$ identify the existence of critical, λ_{cr} and Gaussian, λ_G TFR [1,4]. However in this work we are very interesting in the paracoherent TFR behavior of the magnetoconductivity data situated at $T_{C0}(H) \leq T < T_C(H)$. In this particular temperature range, the TFR of $[\chi_\sigma(T,H)]^{-1}$ data is shown to diverge according to the power law $\Delta\sigma = A_0(t)^{-S_0}$ where A_0 is a constant, S_0 is the critical exponent related to the vortex physics [9] and $t = (T - T_{C0})T_{Co}^{-1}$ where T_{Co} is the superconducting critical temperature which marks the establishment of the zero resistance state. The figure 5 displays the paracoherent region of the $[\chi_\sigma(T,H)]^{-1}$ data to 1kOe ≤ $H \leq$ 50kOe.

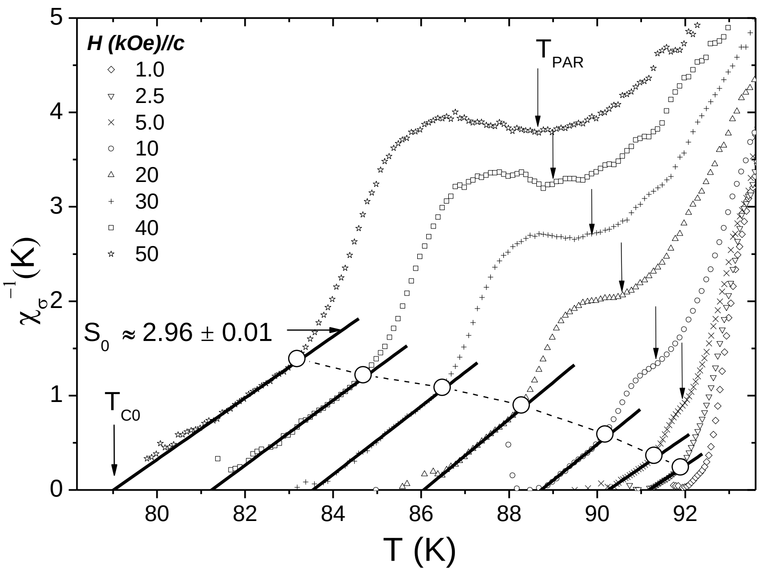

Figure 5. The $[\chi_\sigma(T)]^{-1}$ data of YB(Sr)CO single crystal in the paracoherent region.

In the figure 5 the extrapolation of the solid line of the $[\chi_\sigma(T,H)]^{-1}$ data to the temperature axis allows the simultaneously identification of the critical temperature, T_{C0} and the critical TFR S_0 to $H >$ 1kOe. The T_{C0} decreases faster than T_{PAR} as the applied magnetic field is increasing to 50kOe. The open circles correspond to the temperature maximum amplitude of the lower temperature peak of the figure 3. Otherwise their temperature positions coincide with the beginning of the S_0 power law regimes which identifies it as a precursor of the coupling grain process.

In the immediate vicinity of zero resistance of the $[\chi_\sigma(T,H)]^{-1}$ data is possible identify the occurrence of a power law regime corresponding to the averaged exponent $\overline{S}_0 \approx 2.96 \pm 0.01$. In special, the $S_0 \approx 3$ was observed to a $YBa_2Cu_{2.97}Zn_{0.03}O_{7-\delta}$ single crystal to $H \leq$ 1kOe [1] and to the HTSC polycrystalline samples this exponent converges to 4 as $H >$ 1kOe are applied [4,5].

The identification of an exponent $S_0(H) \approx 3$ in the paracoherent region of the $[\chi_\sigma(T,H)]^{-1}$ data of the figure 5 is compatible with the predictions of the Monte Carlo simulations by Young and Wengel based on the phase glass Hamiltonian presented in the equation (3) [10].

$$H = -\sum_{\langle ij \rangle} J_{ij} \cos(\theta_i - \theta_j - A_{ij}) \quad (3)$$

where J_{ij} is the Josephson coupling energy between nearest neighbor grains i and j, θ_i and θ_j are the phases of the parameter order of the grains i and j, respectively and the vector potential A_{ij} is given to $A_{ij} = (2\pi/\phi_0)\int_i^j \vec{A}.d\vec{l}$ where ϕ_0 is the flux quantum and the line integral is evaluated between the centers of grains i and j. In this scenario the fluctuating phase of the superconductor order parameter in each grain becomes long-range ordered as a consequence of activation of weak links between the grain [5]. This result is the indicative that the coherence transition belongs to the 3D-XY universality class with relevant disorder [9].

According to the results presented in the figures 2, 3 and 5 we suggest that the partial substitution of the 1% of the Ba atoms for Sr atoms introduces a granular character to the superconductor electrical properties of the in the $YBa_2Cu_3O_{7-\delta}$ single crystal. This granular character is highlighted by the two step process of the resistive superconducting transition and the characterization of a paracoherent-coherent transition of the granular array represented by the $S_0(H) \approx 3$ critical exponent.

Acknowledgments

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