Interconnection between zero resistance and magnetic irreversibility temperatures in the hole doped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ single crystal

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Interconnection between zero resistance and magnetic irreversibility temperatures in the hole doped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ single crystal

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Abstract. We report on ac magnetoresistance, $R(T,H)$ and ZFC [$M_{ZFC}(T)$] and FCC [$M_{FCC}(T)$] dc magnetizations measurements of the a hole doped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ single crystal with the propose of to disclose the correlation between the zero resistance, $T_{R0}(H)$ and the magnetic irreversibility, $T_{irr}(H)$ temperatures. The $R(T,H)$ measurements were performed with a PPMS with the measurement current density applied parallel to the sample ab plane. The $M_{ZFC}(T)$ and $M_{FCC}(T)$ measurements were performed with a commercial SQUID magnetometer. For the both measurements $H \leq 50$kOe were applied parallel to the c axis of the sample. The contrasting of the $T_{irr}(H)$ and $T_{R0}(H)$ data profile at H-T diagram shows that for $H \leq 5$kOe the $T_{R0}(H)$ data falls systematically underneath of the $T_{irr}(H)$ data and for $H > 5$kOe the $T_{R0}(H)$ data matches to the $T_{irr}(H)$ data. We attributed to the establishment of a superconducting granular scenario provided for Ca doping as responsible for the observation of these features. At this scenario, $T_{irr}(H)$ and $T_{R0}(H)$ do not depend of the same parts of the sample. While the $T_{irr}(H)$ depends on well coupled grain clusters the $T_{R0}(H)$ depends on grain arrays traversing the whole sample. The granular aspect of this result is discussed at the light of the superconducting glass theories.

Introduction

The magnetic irreversibility of a granular superconductor is characterized by observation of Almeida-Thouless (AT) and Gabay-Toulouse (GT) power laws at low field region of its magnetic irreversibility line (MIL) [1-7]. These power laws are preceded from mean field calculations for the frustrated Ising and Heisenberg spin glass systems [1,4-6]. Otherwise the superconducting resistivity versus temperature transition of a granular superconductor is characterized as a two stage process where the lower temperature one is more affected by the magnetic field [1-3].

In a granular scenario magnetic irreversibility, $T_{irr}(H)$ and zero resistance, $T_{R0}(H)$ temperatures determined from magnetization and resistance measurements respectively are ruled by the physics of superconducting grain coupling [5,7,8]. The $T_{irr}(H)$ depends on the capacity of well coupled grain clusters transport a critical current locally given rise to the magnetic irreversibility [5,7] whereas the $T_{R0}(H)$ is achieved when a long range coherence transition takes place over the coupled grain clusters [5,7]. At the H-T diagram the $T_{irr}(H)$ and the $T_{R0}(H)$ are applied as a boundary to separate the transport of the dissipative current density from the no dissipative one [5,7]. In a homogenous (not granular) superconductor is consensual the idea that the $T_{irr}(H)$ and the $T_{R0}(H)$ temperatures match [7,8] otherwise in a granular (inhomogeneous) superconductor these temperatures are magnetic field dependent and therefore could be not coincident [5,7].

In the present work we reported precisely dc magnetization and ac magnetoresistance measurements performed in a hole doped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ single crystal with the propose of to disclose the correlation between the zero resistance, $T_{R0}(H)$ and the magnetic irreversibility, $T_{irr}(H)$ temperatures in a inhomogeneous $YBa_2Cu_3O_{7-\delta}$ single crystal [2,5].

Sample preparation and experimental procedures

The single crystals of $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ [Y(Ca)BCO] were grown by self-flux method [5]. The selected single crystals were submitted to an extra oxygen process with the objective of improve their superconducting temperature transition, T_C [5]. The picked Y(Ca)BCO sample to the electrical and magnetic measurements had its structure and superconducting transition characterized respectively by x-ray diffraction (XRD) [2,9] and electrical resistance, $R(T,H)$ [2,10]. The figure 1A displays its XRD result. It is possible identify the characteristic YBCO-123 orthorhombic crystalline structure along its c crystallographic axis [11,12]. The *c* lattice parameter obtained from the XRD analysis was $c = (11.68 \pm 0.01)$Å. The $R(T)$ superconducting transition of the Y(Ca)BCO, in the absence of magnetic field, is highlight in the figure 1B. The superconducting temperature transition is defined as the temperature that corresponds to the maximum value of the resistance derivative $[dR(T,H)/dT]$ plot showed in the inset of figure 1B. The single crystal shows a main transition temperature $T_C(H) \approx 89.25K$. The results presented at the figures 1A and 1B to the Y(Ca)BCO single crystal are in agreement with those reported from literature to samples well oxygenated of this material [1,2].

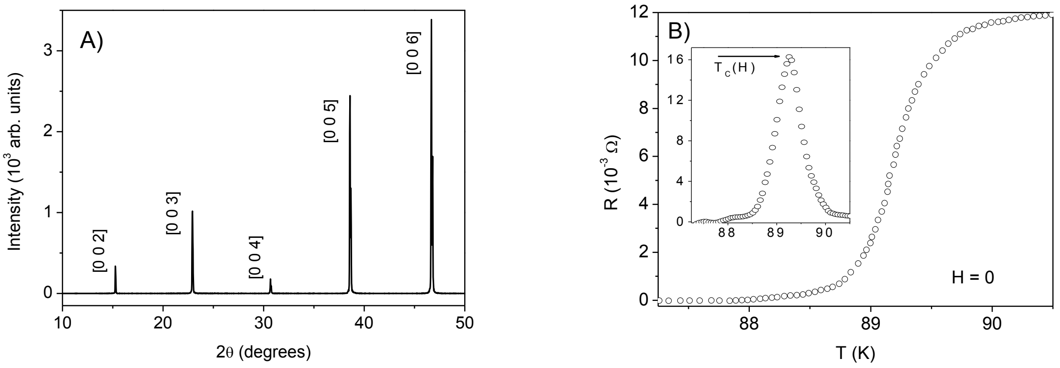

Figure 1. A) The XRD of the Y(Ca)BCO sample obtained for monochromated *CuK α* radiation oriented to its c axis. B) Its $R(T)$ superconducting transition to $H = 0$.

The dc magnetization and ac resistance measurements were performed at the same sample while dc magnetic fields up to 50kOe were applied parallel to its c axis (H // c).

The four contact $R(T,H)$ measurements were performed with ac low current-low frequency PPMS inset to the measurement current density applied along the ab plane of the single crystal.

In special, the contribution of density current intensity to the electrical transport properties of an inhomogeneous superconductor is very relevant [13]. At this work we applied a low excitation dc current density intensity ($J \sim 12$ Acm^{-2} that corresponds to a nominal current of $I = 0.5$mA) to all the magnetoresistance measurements with the proposition of attenuate the contribution of the electrical dissipative effects on the sample magnetoresistance response. The adoption of the last procedure allows us to focus to the majority contribution of the magnetic filed on the electrical inhomogeneous (coupling process) magnetoresistance response of our superconductor.

The $R(T,H)$ data was recorded while the sample was field cooling from $T > T_C$. During it measurements the temperature was swept very slowly (≤ 0.4 K/min) so that a high number of data points could be recorded in the selected temperature range that the temperature resistance derivative $[dR(T,H)/dT]$ could be numerically determinate.

The isofield dc magnetization measurements were performed with a quantum design SQUID magnetometer. The usual zero field cooled, $M_{ZFC}(T)$ and field cooled cooling, $M_{FCC}(T)$ dc magnetizations were recorded. The magnetization measurement proceeds consisted in first cooling down the sample to temperatures well below T_C in zero field (ZFC). Then the zero field cooled magnetization, $M_{ZFC}(T)$ was measured under constant magnetic field while slowly warming the sample (0.4 K/min or less) up to temperatures well above T_C. Subsequently the field cooled cooling magnetization, $M_{FCC}(T)$ was measured while cooling (0.4 K/min or less) the sample back to low temperatures in the same field (FCC).

Experimental results and discussion

The figures 2A and 2B display in their main the $\Delta M(T)$ and $dR(T,H)/dT$ plots to H = 1kOe where the $T_C(H)$, $T_{R0}(H)$ and $T_{irr}(H)$ temperatures are in eminence. Otherwise their insets highlight the correspondingly $R(T,H)$ data $M_{FCC}(T)$ and $M_{ZFC}(T)$ curves.

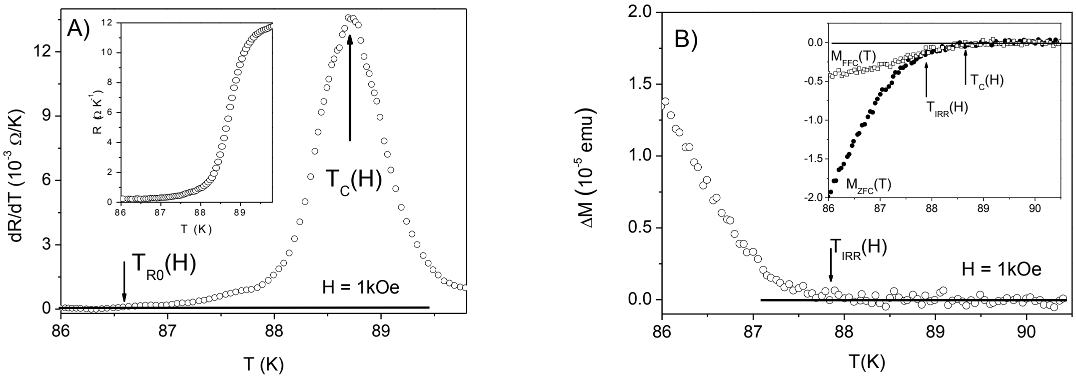

Figure 2. The determination of A) $T_{R0}(H)$ and B) the $T_{irr}(H)$ limits when the H = 1kOe is applied parallel to the c axis of the Y(Ca)BCO single crystal.

The figures 2A and 2B illustrates the method adopted to the determination of $T_{R0}(H)$ and $T_{irr}(H)$ temperatures. The $T_{R0}(H)$ is the temperature value that approximately sets the deviate from the zero base line of the $dR(T,H)/dT$ plot in the main figure 2A. The same analogous proceed is applied to the determination of the $T_{irr}(H)$ determined from the $\Delta M(T)$ plot $[\Delta M(T) = M_{FCC}(T) - M_{ZFC}(T)]$ of the figure 2B.

Other aspect of the results showed in the figure 2A is the temperature asymmetric of the $dR(T,H)/dT$ data. It is possible identify in the figure 2A that the temperature resistance transition of the Y(Ca)BCO sample is characterized by a main peak with a hump at its lower temperature side. When its behavior is contrasted to the inset $dR(T,H)/dT$ data result of the figure 1B is possible to point the effect of the magnetic field. While the main peak of $dR(T,H)/dT$ data is smoothly affected for the enhancement of the applied field the hump at its lower temperature side is affected by it becoming more prominent as the applied magnetic field strength is enhanced. The classification of the superconductor magnetoresistance transition as a two stage process with the lower temperature step more affected by the magnetic field represents the signature of a granular superconductor [1-5]. In this scenario while the $dR(T,H)/dT$ peak marks the pairing critical temperature $T_C(H)$ within the superconducting grains, the hump is connected to the grain coupling and the coherence transition of the granular system. An applied field is well known to distort the phase of the GL order parameter within the junctions between the grains thereby weakening the coupling energy and the pinning strength of the Josephson flux dynamics while lets almost intact the superconducting transition within the grains governed by the Abrikosov flux dynamics [5-8].

The $T_C(H) \approx 88.8$K estimated from ac resistance and the dc magnetization, inset of figure 2B, measurements to $H = 1$kOe is in agreement. Otherwise very different were the $T_{R0}(H) \approx 86.65$K and $T_{irr}(H) \approx 87.8$K values determined to the same applied field. This is the first symptom that a coupling grain process reacts in a different way in an inhomogeneous superconductor and it does not matter if the superconductor is a single crystal. In other to disclose the correlation between magnetic irreversibility and zero resistance state of the $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ single crystal we plot the $T_{irr}(H)$ together with the corresponding $T_{R0}(H)$ data in the figure 3 where the inset stressed the low field behavior.

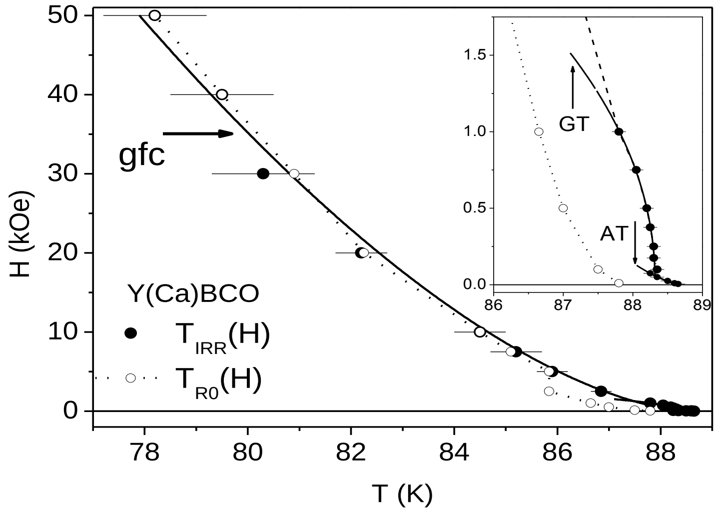

Figure 3. The correlation between the $T_{R0}(H)$ (open symbols) and $T_{irr}(H)$ (closed symbols) data of the Y(Ca)BCO sample. The inset highlight the low field details of this correlation.

In the figure 3 the solid lines identified as gfc, GT and AT are $T_{irr}(H)$ fittings with the general power law [1-5,7]:

$$H(T) = H_0\left(1 - \frac{T_{irr}\,(H)}{Tirr\,(0)}\right)^{\alpha} \qquad (1)$$

In equation 1 the $T_{irr}(H)$ $T_{irr}(0)^{-1}$ is the reduced temperature, H_0 and $T_{irr}(0)$ are fitting parameters whose are respectively the irreversibility field at zero temperature and the extrapolation of $T_{irr}(H)$ to zero field. The adjusted fitting parameters to the gfc fit were $\alpha = 1.60\pm0.13$, $H_0 = 1484$kOe and $T_{irr}(0) = (88.55\pm0.35)$K for the AT fit were $\alpha = 1.60\pm0.18$, $H_0 = 304$kOe and $T_{irr}(0) = (88.55\pm0.35)$K and for the GT fit were $\alpha = 0.48\pm0.01$, $H_0 = 12$kOe and $T_{irr}(0) = (88.32\pm0.04)$K.

The gfc continuous line through the $T_{irr}(H)$ data in the high field region ($H \geq 5$kOe) 3 is fittings with the power law [$\alpha = 3/2$ in the equation 1] predicted for the magnetic irreversibility line (MIL) by the giant-flux-creep (gfc) theory [1-5] and it is consider the signature of the intragranular Abrikosov flux dynamics [1-5,7].

The MIL in the low field region of the inset of figure 3 is adjusted by the Almeida-Thouless (AT) [1-5] [$\alpha = 3/2$ in the equation 1] and the Gabay-Toulouse (GT) [1-5] [$\alpha = 1/2$ in the equation 1] power laws. Although the AT power law has the same form as the gfc power law its physical background and the fitting parameters are quite distinct [1-5]. The description of the low field region of the MIL our sample by the AT–GT power laws is not a surprise since the grain coupling in grain aggregates of disordered superconductors under applied magnetic field are well known to be dominated by frustration, likewise the spin coupling in spin-glass systems [1,2,4]. In this scenario our Y(Ca)BCO single crystal can be described as a frustrated superconducting grain aggregates where the Josephson flux dynamics dominates [1,2,4].

The principal result of the present work is summarized when we emphasize, within our experimental precision, the correlation between the $T_{R0}(H)$ data and the MIL behaviour in the H-T diagram of the figure 3. It is possible to identify that at low field region ($H \leq$ 5kOe) the $T_{R0}(H)$ data fall systematically below the MIL (see inset) as projected to take place to an granular superconductor. In a granular scenario when low fields are applied the starting of magnetic irreversibility is observed when the first closely packed of the aggregates of grains gets to trap vortices and blockade the magnetic flux mobility. These coherent grain clusters may remain disconnected from each other because of weaker links that are resistive down to lower temperature. A macroscopic superconducting state only stabilizes when tunneling of the Cooper pairs becomes strong enough to enforce a percolation coherence transition in the granular superconducting array justify the observation of the $T_{irr}(H) > T_{R0}(H)$ in the low field region of the Y(Ca)BCO sample H-T diagram.

The $T_{irr}(H)$ and $T_{R0}(H)$ correlation showed in the figure 3 to the $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ single crystal complements and magnify the preliminary results in this theme obtained to a $Y_{0.98}Ca_{0.02}Ba_2Cu_3O_{7-\delta}$ single crystal in the low field limit ($H \leq$ 0.5kOe) [2]. The results displayed in the figure 3 suggests that the $T_{irr}(H)$ and $T_{R0}(H)$ correlation could be applied as a efficiently tool to separate the Josephson and Abrikosov flux dynamics ascendancy in the H-T diagram of an inhomogeneous superconductor.

In this work we reported ac magnetoresistance and dc magnetization measurements with the propose of the disclose the correlation between the zero resistance state and magnetic irreversibility in a hole doped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ single crystal. The magnetoresistance transition and the magnetic irreversibility line behaviours show that the 10% partial substitution of the Ba atoms for Ca atoms introduces a superconducting granular character to the electrical and magnetic properties of the $YBa_2Cu_3O_{7-\delta}$ single crystals. The correlation between the $T_{R0}(H)$ and $T_{irr}(H)$ data shows that electrical transport remains dissipative for $T_{R0}(H) \leq T < T_{irr}(H)$ while $H \leq$ 5kOe are applied parallel to the c axis of the single crystal.

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