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Superconductor-insulator transition induced by nanodefects in Y:123 bulk HTS

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The transition from superconductor to insulator was induced by partial substitution of Cu by Fe and by controlling oxygen content in $YBa_2(Cu_{0.96}\,Fe_{0.04})_3O_y$ superconductor The effects of nanoscale defects induced by iron clusters and by oxygen content on the electrical resistance of underdoped system were studied. The origin of insulator behavior on electrical resistance above the superconducting transition is analyzed by using different localization mechanisms for mobile carriers.

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1. Introduction

It has been shown that the critical transition temperature of $YBa_2Cu_3O_{7-\delta}$ is strongly influenced by the oxygen content. In $YBa_2Cu_3O_{7-\delta}$ the decrease of hole concentration by increasing oxygen deficiency from $\delta=0$ to $\delta=1$ lead to the increase of apical oxygen distance to Cu (2)O_2 plane. It has been well established that already small concentrations of hole doping in CuO_2 planes reduces rapidly the AF ordering temperature. There is a strong tendency for an AF to expel holes, which lead to phase separation into a hole rich and hole -poor phase [1]. For the heavily underdoped $YBa_2Cu_3O_{7-\delta}$ ($\delta=0.68$ and 0.7) single crystal, a hysteresis was observed up below 20 K in the magnetoresistance curve as a function of magnetic field. This result was explained by assuming a developed array of charged stripes and by the fact that the magnetic field induces a topological ordering in the stripes [2]. The Fe cations substitute mainly in Cu(1) chains and are grouped together to form clusters. For low concentration of Fe (3-5at% Fe) the cluster shape must be linear and the distance between the linear clusters is large [3]. The effect of oxygen content and the thermal treatment on the electrical resistance of underdoped Y:123 bulk system was studied. The results were discussed in relation to the fragmentation and stripe pinning in Cu(2)O_2 planes as a result of the disorder produced by the Fe clusters in Cu(1)O chains [4,5].Recently, neutron scattering measurements on $YBa_2Cu_3O_{7-\delta}$ (δ=0.85, 0.65, 0.4 and 0.1) single crystal suggest the presence of spatial inhomogeneities and microscopic electronic phase separation in superconducting material [6].

In this work, we present the influence of partial substitution of Cu by x=0.04 Fe on the microstructure and the influence of oxygen deficiency on the evolution of electric resistance function of temperature in underdoped samples $YBa_2\,(Cu_{0.96}\,Fe_{0.04})_3O_{7-\delta}$ samples with δ=0.45; 0.25 and 0. The origin of insulator behaviour above the superconducting transition is analyzed by using different localization mechanisms for mobile carriers.

2. Experimental

A series of $YBa_2\,(Cu_{0.96}\,Fe_{0.04})_3O_{7-\delta}$ samples were prepared by using solid state reaction method for CuO,Y_2O_3,$BaCO_3$ and Fe_2O_3 [4].

The standard iodometric titration, shows in our x=0.04 Fe doped Y:123 samples the values δ=0.45 ;0.25 and 0.00 for the oxygen content.

X-ray diffraction measurements show that all samples are single phase of Y:123 systems with a tetragonal structure.

The measurements of microstructure were performed with a optical microscope of the type Neophot using polarized light.

The scanning electron microscope (SEM) equipped with an X-ray energy dispersive analyzer were used for study the global and local chemical composition of the samples.

Electrical resistance was measured by using the standard four-point method. Gold wires were attached with silver paste on the samples. The electrical contact resistivity was typically less than $2\times10^{-4}\ \Omega\,cm^2$. The current intensity passed through sample was between 1mA and 10 mA.

Modeling of the isotherms in our samples reveal that iron form nanoclusters in the [110] and [$1\bar{1}0$] directions, where Fe is in a 4+ pyramidal coordination [7]

3. Results and discussion

The picture shown in Fig. 1, obtained by optical microscope with a magnification of 1300, is representative of all samples for the grain distribution. The average grain sizes were 7 μm and the size distributions starts at nearly 2 μm. This result agree by the measurements of Diko and Schroeder [8,9] on the $YBa_2\,(Cu_{0.97}\,Fe_{0.03})_3O_y$ samples.

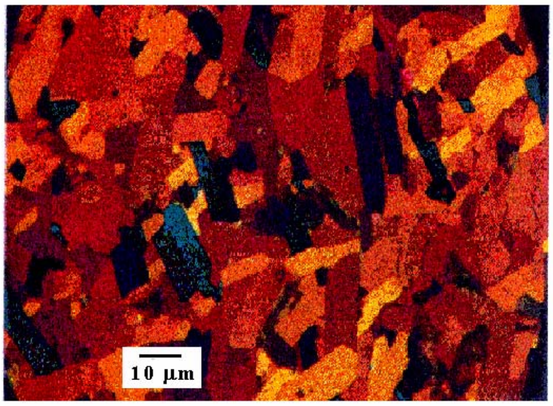

Fig. 1.The microstructure of Y:123 Fe doped samples obtained by optical microscope.

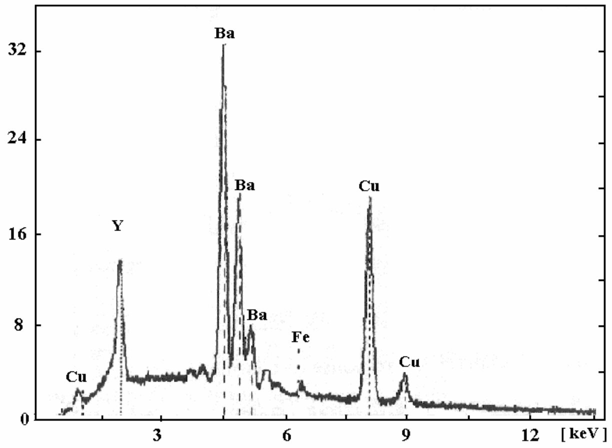

Fig. 2. EDX spectra obtained for $YBa_2(Cu_{0.96}Fe_{0.04})_3O_{7-\delta}$ (δ=0.45) sample.

Fig. 2 show the EDX spectra on a large area of sample with δ=0.45. The EDX analysis confirmed that the samples are homogeneous, because the global composition is the same as the local composition obtained by SEM at different places of the sample. The global iron content is around 4% of the total amount of Cu.

Electrical resistivity function of temperature shows the insulating behavior in normal state above the superconducting transition, and the critical transition temperature T_c increases from 18 K and 36 K by decreasing δ from 0.25 to 0.00.

The transition from superconductor to insulator is attributed to some kind of localization. Our previous studies on Bi:2201 thin films [10] shows that in the low temperature region, the VRH (variable range hopping) model does not explain the localization in our samples.

A log (1/T) behavior of ρ(T) was previously observed in BSLCO thin films with various oxygen concentrations, respectively [11,12] and in underdoped superconducting LSCO [13] and BSLCO [21] both in a 60 T magnetic field . To check the validity of this observation in our Fe doped Y:123 bulk systems, in Fig. 3 electrical resistance were replotted vs. lnT for underdoped samples with oxygen deficiency δ=0.25 and δ=0.45, respectively.

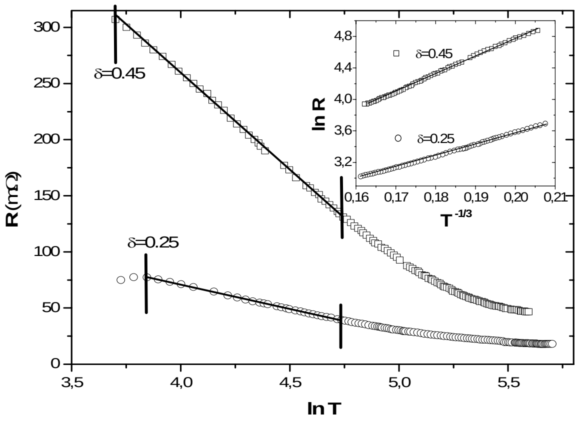

Fig. 3. Electrical resistance versus lnT. The vertical lines show the temperature range for linear dependence of electrical resistance versus lnT, for samples with δ=0.25 and 0.45.The insert shows the validity of VRH processes in high temperature range.

The plot gave almost a straight line below 110K. The origin for the increase of electrical resistance may be in the localization of mobile carriers because of the disorder in the crystal potential induced by oxygen.carriers The logarithmic temperature dependence of electrical resistance was obtained taking into consideration a model of strong correlated electronic system with a single particle self-energy of the marginal Fermi liquid, and in the presence of randomly distributed nonmagnetic impurities, [14].

The density of states has the form of power law energy dependence: $N(\varepsilon) = C\ \varepsilon^{\alpha}$,where α is a phenomenological coefficient that strongly affects the temperature dependence of the electrical resistivity The electrical resistivity is influenced by phenomenological parameter α as, [15]:

$$\rho(T) \sim [\ln(1/T)]^{2/(1-\alpha)}. \qquad (1)$$

The model fits our experimental data for a α value close to -1, and suggests that electron correlations lead to a singularity in density of states.

Another process which explain the charge transport at low temperature is the variable -range -hopping (VRH) among the localized states near the E_F [16, 17].

This is a process in which an electron at an occupied localized state near E_F receives energy for a phonon that enables it to “hop” to a nearby empty state at energy near E_F. The VRH resistance is of the form:

$$R = R_0 \exp[(T_0/T)^{\alpha}] \qquad (2)$$

with T_0 a characteristic temperature and α a constant that is determined by the precise conditions of hopping processes. VRH conduction provides direct evidence of the existence of empty localized states near E_F. The characteristic temperature T_0 in VRH processes in three dimensions is of the form: $T_0 = 16/[N(E_F)\,k_B L_{loc}^3]$, where L_{loc} defines the localization length and $N(E_F)$ the density of states nears the Fermi level. The expression for coefficient α is:$\alpha = (n+1)/(n+D+1)$, where D show the dimension of problem.

By assuming that $N(E_F)$ is energy independent (n=0) we obtain the case of Mott variable range hopping with α =1/3 and α =1/4 in 2D and 3D dimension respectively

The VRH model does not explain the localization processes below 110 K in our samples.

In the insert of Fig. 3 the electrical resistance of samples is plotted logarithmically versus T^{α} for temperatures above 110 K. From this figure is clear that α = 1/3 some linearity behavior is obtained. This result suggests the existence of the crossover temperature from VRH processes to localization processes dominated by lnT dependence of electrical resistance at low temperatures.

4. Conclusions

The experiments have been performed on samples with nanoscale defects induced in the charge reservoir by the partial substitution of Cu by 4% Fe and by oxygen deficiency.

The microstructure analysis and EDX measurements shows that the samples are monophasic compounds and the global content of iron which substitute Cu is around 4%.

By the control of oxygen content (δ=0.00; 0.25 and 0.45), the bulk underdoped $YBa_2(Cu_{0.96}\ Fe_{0.04})_3O_{7-\delta}$ superconducting samples with critical transition temperature T_c between 18 K and 36 K were obtained.

Electrical resistance as a function of temperature show for all samples an insulating behavior in the normal state.

In high temperature range (110 K - 220 K), the temperature dependence of electrical resistance is well explained by VRH processes (for y=0.25 and δ=0.45).

In the low temperature range a *lnT* dependence of electrical resistivity was evidenced.

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