Normal state resistivity of BSCCO single crystals: description with a two barriers model

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Abstract

We present dc resistivity multiterminal measurements performed in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal. Sample doping was varied from underdoped to slightly overdoped. Data are analyzed in term of a model which assumes two different mechanisms for the out-of-plane conduction, markedly thermal activation and incoherent tunneling. Within this model we are able to describe data of normal state resistivity. We also analyze data from the literature. In all cases, the proposed model describes very well the data in the normal state.

Key words: Cuprates; $Bi_2Sr_2CaCu_2O_8$; normal state; dc resistivity

1. Introduction and model

The understanding of the nature of the c-axis normal state transport in the copper oxide superconductors represents a key element in the theories of the superconducting state.[1]
In this paper we present a phenomenological model able to account the main features of the c-axis resistivity (ρ_c) behaviors in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) at different doping levels.
The model is founded on the following assumptions:
- an electron moving along the c axis experiences a series of potential barriers due the layered structure of BSCCO;
- two kinds of barriers are present, one produced by the Ca layers separating the CuO_2 bi-layers in each cell and the other by the BiO/SrO plans in between each bi-layers (see Fig.1).
- for each barrier two mechanisms contribute to the interlayer transport:
i) incoherent tunneling of the charge carriers [2];
ii) thermal activation of the charge carriers above the barrier, with doping dependent energy Δ.

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As for the point *i)* we make use of the model described in Ref.[2]: if the characteristic time for the tunneling is much less than the time between collisions in the plane, it can be shown [2] that the resulting ρ_c depends linearly on the in-plane resistivity ρ_{ab}, that is $\rho_c^{(t)} = \frac{1}{\sigma_c^{(t)}} = \alpha + \beta\rho_{ab}$ where α and β depend on the unit area density of states and on the structural defects always present. For the second transport mechanism we consider a standard calculation for thermally activated transport through a barrier, which gives the conductivity $\sigma_c^{(th)} = \sigma_0 e^{\frac{-\Delta}{T}}$. Putting together the two contributions to the conductivity for any barrier, one gets:

$$\sigma_{c,i} = \sigma_{c,i}^{(th)} + \sigma_{c,i}^{(t)} = \frac{1}{\alpha_i + \beta_i\rho_{ab}} + \sigma_{0,i} e^{\frac{-\Delta_i}{T}} \qquad (1)$$

where the suffix i stands for the *i-th* barrier, Δ_i is the energy barrier, and $\sigma_{0,i}$ is a coefficient proportional to the number of carriers. The final expression for the c-axis resistivity that will be used in fitting the data becomes:

$$\rho_c = \frac{1}{\sigma_{c,1}} + \frac{1}{\sigma_{c,2}} \qquad (2)$$

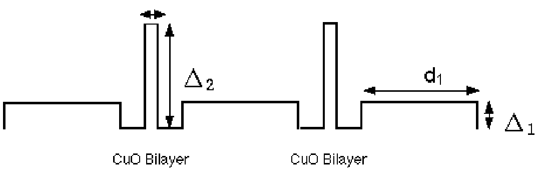

Fig. 1. Schematic of the barriers employed in the model.

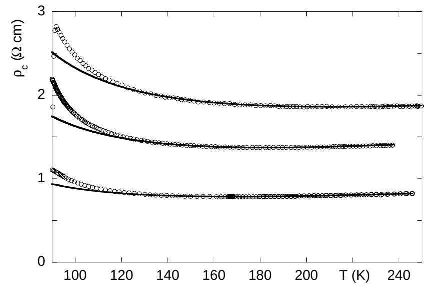

Fig. 2. ρ_c *vs* T (open circles) in the slightly overdoped samples. The full lines represent fits by Eq.2.

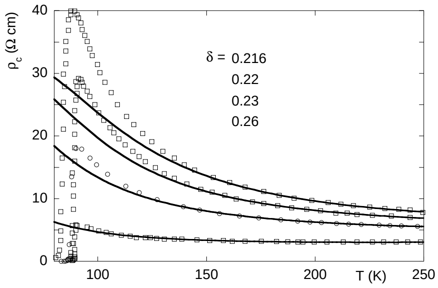

Fig. 3. As in Fig.3, for a different range of δ. Apart the curve at δ=0.23, data are digitized from Ref.[6]. Open circles: our data; open squares: data from Ref.[6].

2. Experimental result and discussion

To obtain simultaneous measurements of ρ_c and ρ_{ab} on the same sample we have performed multi-terminal voltage measurements as a function of the temperature on BSCCO single crystals at different doping level. Details on crystals growth and doping can be found in Refs. [3] and [4].

Using $25\mu m$ gold wires and silver paste, eight low resistance contacts ($\sim 2 \div 10\Omega$) were attached on each of the samples, four on each of the wide surfaces. Voltage was always detected using a four-probe technique, choosing a pair of leads as current contacts and simultaneously detecting three voltages from the other pairs of wires by means of sensitive nanovoltmeters. As described elsewhere [5], from three simultaneous voltage measurements we are able to consistently derive both ρ_c (see Fig.s 2 and 3) and ρ_{ab}, additionally checking for the presence of sample inhomogeneities.

Here we want to stress that our goal is to check the capability of the model of catching the main features of the data. As a consequence, in this paper we focus on an oversimplified version of our model, in which fluctuation effects given by the approaching the superconducting transition and/or the opening of the pseudogap will be neglected.

Making reference to Fig.1, we use also the following approximations: we neglect the tunnel conductivity through the largest barrier, and the thermally assisted conductivity across the highest barriers. The (a,b) plane resistivity is obtained through a linear fitting of the data at high temperatures, extrapolated down to T_c. Within this simplified picture, we are able to obtain the fits as reported in Fig.2. The proposed model captures several of the main, puzzling features of ρ_c. In particular, it is able to reproduce the numerical values of the resistivity, as well as the change of the shape of the curve: from monotonously increasing (underdoped samples) to a nonmonotonic behavior, with a minimum at rather high temperatures.

As a second, important check the same fit procedure has been adopted, on the digitized data from Watanabe et al. [6], (see Fig.3) and again good results are obtained.

As regarding the fits it is to be noted that the predictions of the model always understimate the ρ_c resistivity when approaching T_c. This is consistent with the fact that in our model we neglect the effects of the reduction in the charge tunneling probability due to pseudogap opening and/or superconducting fluactuations. The possible inclusion of these effects in the model together with an analysis of the doping dependence of the involved parameters will be considered in future works.

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