Physica C 470 (2010) S989–S990

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Competing orders and the resistivity curves of cuprate superconductors

E.V.L. de Mello [a,*], C.F.S. Pinheiro [b]

[a] Instituto de Física, Universidade Federal Fluminense, Niterói, RJ 24210-340, Brazil
[b] Departamento de Física, Univ. Federal de Ouro Preto, Ouro Preto, MG 35400-000, Brazil

ARTICLE INFO

Article history:
Accepted 6 November 2009
Available online 11 November 2009

Keywords:
Cuprates superconductors
Random resistor network
Resistivity calculations

ABSTRACT

The resistivity as function of temperature of high temperature superconductors (HTSC) is an important property of cuprates but it still lacks a widely accepted explanation. Here we show that the overall behavior of an entire series can be explained by calculations using an electronic phase segregation into two main component phases.

In opposition to the low temperature superconductors that the normal phase is a well known Fermi liquid, the normal phase of HTSC has many non understood properties. Here we want to show that the particular behavior of $R(T)$ for different compounds of a single series is a manifestation of the intrinsic inhomogeneity of these materials. We can divide the resistivity behavior for a system in three general types: It falls linearly with the temperature for samples in the overdoped regions [1]. It falls below the linear trend for compounds near the optimum values as measured by several groups [2,3]. For very low doping it falls down with the temperature, reaches a minimum at an intermediate temperature, starts to increase at lower temperature until it reaches a local maximum, an then it drops to zero below T_c. This reentrant behavior is observed in almost all underdoped cuprates [4] but its origin has not been very much discussed in the literature. The significance and origin of such rich phenomena will be the focus of our work.

To deal with this problem we consider the general phase separation theory of Cahn–Hilliard (CH) [5]. It describes how a system evolves from small fluctuations around an average density p to a complete separation into low and high density regions. At each of these small regions we associate a local resistivity derived from the work of Takagi et al. [1] on the LSCO series ($La_{2-p}Sr_pCuO_4$) to a large range of values of T and p. Then we use the random resistor network (RRN) method [6] to derive the system resistivity as a function of the temperature $R(T)$. The local density and resistivity is randomly picked and the final $R(T)$ result is an average of many different configurations.

On the other hand, electronic phase separation (EPS) appear to be an universal feature of HTSC. It is seen in the form of stripes by neutron diffraction [7] and in many BSCO samples by STM [8]. The possible origin of this EPS transition is the proximity to the insulator AF phase, common to all cuprates, as we derived from the principle of the competing minimum free energy [9].

The RRN model has been widely used to study disordered systems, percolation and conductance models [10] and it fits well our purpose. Our system is the Cu–O plane modelled by a 100×100 square lattice of nodes connected by resistors, each one representing a nanoscopic domain with different orders that could be metallic, superconducting or insulating (AF phase), their distribution depending on temperature and composition.

At high temperature the total resistance is a linear function of temperature [1–3]. At low temperature phase separation begins at T_{PS} and two bands of different compositions appear. These bands have their central values Δp apart and are $\delta p(i)$ wide (see Fig. 1). Both $\Delta p(i)$ and $\delta p(i)$ depend on temperature and are all symmetric to average composition p as in Fig. 1 for $p = 0.07$ [9].

From the results of Takagi et al. [1], for various compositions p and a given temperature, is possible to devise a nearly exponential dependence on the composition p. The metallic links in the RRN will then follow a random distribution in the allowed values of $p(i)$ (the bands) and their resistances will be given by a function derived from the values of Takagi et al. [1]

$$R(p(i), T) = A(T)\exp\{-B(p(i) - p)\} \tag{1}$$

where $B = 0.05$ and $A(T)$ are derived directly from the LSCO series measurements [1].

As in Fig. 1, below $T_{on}(p)$, a fraction of the conducting metallic links (largest $p(i)$'s) becomes superconducting (SC) links and this fraction reaches 100% of the metallic band at $T_c(p)$ where the resistivity vanishes. Similarly, insulator links appear in the low density band as $p(i) \leqslant 0.05$ as can be seen in Fig. 1.

* Corresponding author. Tel.: +55 21 26295822; fax: +55 21 26295882.
E-mail address: evandro@if.uff.br (E.V.L. de Mello).

0921-4534/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2009.11.056

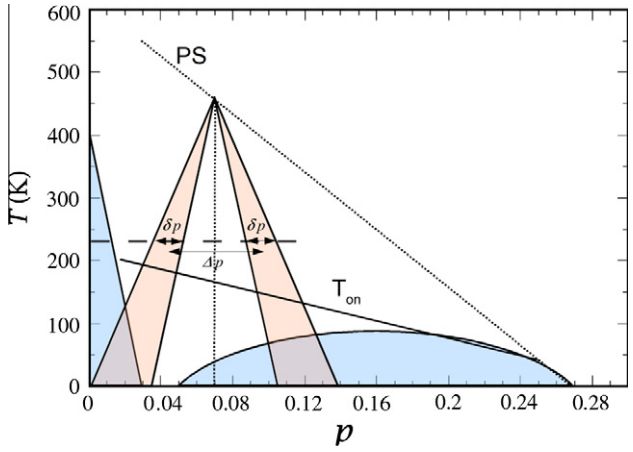

Fig. 1. Schematic phase diagram showing the onset of phase separation at T_{PS} where the bimodal bands of doping fractions $\delta p(i)$ start. These bands set the local granular densities $p(i)$ used in calculations. It is also shown the onset of superconducting grains at T_{on}.

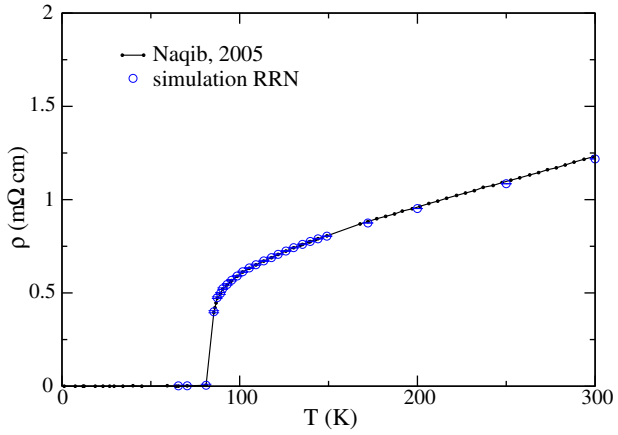

Fig. 2. Data points from Naqib et al. [2] for a $p \approx 0.14$ compound, with the linear behavior just to $T_{on} \sim 180$ K where the superconducting grains with higher local critical temperature appear. The continuous line is our calculations.

Results of simulations for typical samples near optimum doping are shown in Fig. 2 for the compound $Y_{0.80}Ca_{0.20}Ba_2Cu_3O_{7-\delta}$ with average doping $p = 0.136$. 300 samples were used for each point in the graph. The phase separation begins at 400 K; SC links of resistivity 10^{-8} mΩ cm^{-1} are introduced below 180 K, according to the $T_{on}(p)$ line, and generates the down turn in the resistivity that deviates from the linear behavior.

For low doping materials the resistivity requires special care because it contains insulator, metallic and superconducting regions represented by links in the RRN method. Thus for the $p = 0.07$

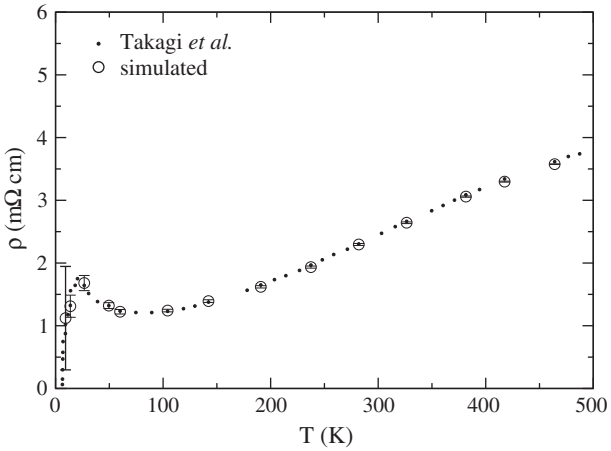

Fig. 3. Simulation results (circles) for the resistivity of $La_{2-p}Sr_pCuO_4$ with $p = 0.07$ with $T_{on} \sim 280$ K and the reentrant behavior, common to all lighted doped samples. Dots represent experimental data obtained by Takagi et al. [1].

we find a reentrant complex behavior, due to the mixture of SC and insulator regions in the two different bands. The appearance of the insulator regions ($\rho = 200$ mΩ cm^{-1}) in our RRN matrix occurs when $\delta p(i)$ crosses the value of $p(i) \leqslant 0.05$ [4] at low temperatures as it is demonstrated in Fig. 3. This is the reason why, at low temperatures, the resistivity increases, but eventually, as it decreases further and crosses T_{on}, the metallic resistors become superconductors (resistivity 10^{-8} mΩ cm^{-1}) and the resistivity vanishes due to the percolation among the superconducting regions, as we explained above. This behavior is the same for the compounds just above the threshold value of $p = 0.05$.

As $T \to 0$ both insulating and SC links fractions come close to the link percolation threshold 0.50, what is the reason for the strong variation expressed in the error bars as $T \to 0$ in Fig. 3.

Acknowledgements

We gratefully acknowledge partial financial aid from Brazilian agencies CNPq and Capes.

References

[1] H. Takagi et al., Phys. Rev. Lett. 69 (1992) 2975.
[2] S.H. Naqib et al., Phys. Rev. B71 (2005) 054502.
[3] C.A. Passos et al., Phys. Rev. B 74 (2006) 094514.
[4] Seongshik Oh et al., Phys. Rev. Lett. 96 (2006) 107003.
[5] D.N. Dias et al., Physica C468 (2008) 480.
[6] S. Kirkpatrick, Rev. Mod. Phys. 45 (1973) 574.
[7] J.M. Tranquada et al., Nature (London) 375 (1995) 561.
[8] Abhay N. Pasupathy et al., Science 320 (2008) 196.
[9] E.V.L. de Mello et al., J. Phys.: Condens. Mat. 21 (2009) 235701.
[10] J.S. Andrade et al., Phys. Rev. B 54 (1996) 3910.