Codoping Effect of Zn and Pr in YBa$_2$Cu$_3$O$_{7-\delta}$

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In this paper we present the resistivity data for Pr and Zn codoped compound Y$_{1-x}$Pr$_x$Ba$_2$[Cu$_{1-y}$Zn$_y$]$_3$O$_{7-\delta}$ with $0 < y < 0.1$ and $x = 0.0$, 0.1 and 0.2. The data is analysed in terms of the superconducting critical temperature T_c, residual resistivity ρ_0 and the resistivity slope $\mathrm{d}\rho/\mathrm{d}T$ corresponding to the linear ρ–T region. It is found that for $x = 0.1$ Pr has a minimal influence on the in-plane processes for Zn impurity alone affecting slightly T_c and ρ_0. The slope $\mathrm{d}\rho/\mathrm{d}T$ becomes larger for $0.03 < y < 0.06$ leading to larger depining effect and hence slower fall of T_c as a function of y. For $x = 0.2$ there is a drastic change, ρ_0 becomes abnormally large, $\mathrm{d}\rho/\mathrm{d}T$ becomes negative implying absence of depinning and a totally pinned charge stripes. Superconductivity vanishes at $y = 0.03$. It is concluded that for $x = 0.2$ Pr converts the system from overdoped to underdoped region leading to the universal superconductor–insulator transition.

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1. Introduction

Different impurities in cuprate superconductors degrade the critical temperature in different ways. In doing this they shed some light on the electronic state of the superconductor. The joint effect of two different impurities is not the same as the sum of the effects of individual impurities. In this work we report the effect of Pr and Zn in YBa$_2$Cu$_3$O$_{7-\delta}$ Y-123 system. It is known that Zn substitutes at Cu(II) [1–6] site in the CuO$_2$ plane. It is a non-magnetic impurity and degrades T_c by potential scattering [7–9] which results in pinning the charge stripe [10, 11]. Superconductivity vanishes at about ten percent of Zn. On the other hand, Pr substitutes the Y site and is responsible for forming a narrow band called Fehrenbacher and Rice (FR) band [12] near the Fermi energy. This band grabs holes from the p–d band in the plane resulting in T_c degradation [13]. There are three regions in terms of Pr concentration (x). For $0 < x < 0.1$ the system makes transition from overdoped to underdoped state and T_c as a function of x decreases very slowly. For $0.1 < x < 0.5$ the main process is hole depletion and T_c decreases faster. For $x > 0.5$ there is an additional process of magnetic pair breaking and T_c goes to zero rapidly. In this work we present resistivity versus temperature results for varying Zn concentration (y) for two values of Pr concentrations $x = 0.1$ and $x = 0.2$ and study the codoping effects in the two regions mentioned above. The data is analysed in terms of T_c, ρ_0, $\mathrm{d}\rho/\mathrm{d}T$.

2. Experimental

The polycrystalline samples with composition of Y$_{1-x}$Pr$_x$Ba$_2$[Cu$_{1-y}$Zn$_y$]$_3$O$_{7-\delta}$ with different values of x and y ($0 \le x \le 0.20$ and $0 \le y \le 0.10$) were prepared by solid-state reaction method. The ingredients, Y$_2$O$_3$, BaCO$_3$, CuO, ZnO, with/without Pr$_6$O$_{11}$ of purity 99.99% taken in the stoichiometric ratio were thoroughly mixed, ground and calcined at 920°C in air for a period of 17–20 h. After four intermediate grindings and calcinations in air the precursors so obtained were reground and pressed to pellets, and sintered in oxygen for 24 h at 940°C and then furnace cooled to below 100°C with an intervening annealing for 24 h at 600°C [14]. The samples were characterised by X-ray diffraction (XRD) using Cu K_α radiation and the phase purity of the samples was checked using the Rietveld refinement. The structure for the entire series is found to be orthorhombic and X-ray diffraction patterns are presented in Fig. 1a–c. The oxygen content was determined by iodometric titration which is found to be 6.7 ± 0.1 [15]. The resistivity was measured in the temperature range 14–300 K, using standard four probe technique coupled with a close cycle refrigerator.

3. Results and discussion

Resistivity curve $\rho(T)$ for $x = 0, 0.1$, and 0.2 samples are presented respectively in Fig. 2a–c. One can see that for $x = 0$, T_c disappears at $y = 0.1$ but the linearity in the curve is retained. Whereas for $x = 0.1$, $\rho(T)$ curve shows non-linear behaviour at $y = 0.1$ and for $x = 0.2$ the non-linearity in $\rho(T)$ curve starts at $y = 0.03$. This behaviour of T_c for different concentration of Zn and Pr is presented in Fig. 3. The linear part of ρ–T curve is fitted to the equation $\rho = \rho_0 + \rho_1 T$. The intercept ρ_0, called residual resistivity corresponds to the impurity scattering that leads to the pinning of charge stripe [14] and the slope ρ_1
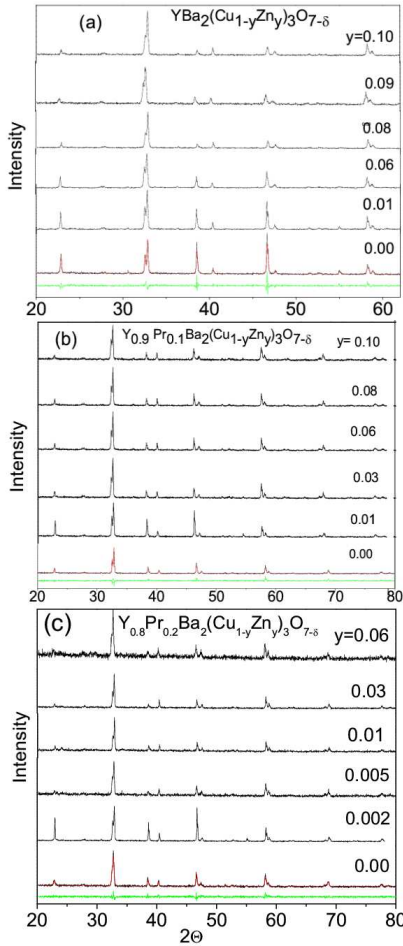
Fig. 1. X-ray diffraction patterns of $Y_{1-x}Pr_xBa_2[Cu_{1-y}Zn_y]_3O_{7-\delta}$ (a) for $x = 0$, (b) for $x = 0.1$ and (c) for $x = 0.2$.
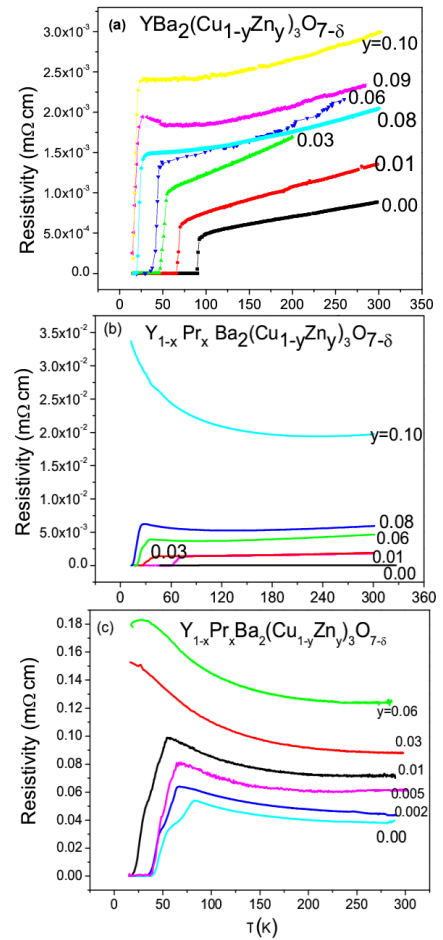

Fig. 2. Resistivity vs. temperature for $Y_{1-x}Pr_xBa_2[Cu_{1-y}Zn_y]_3O_{7-\delta}$ samples with different values of Zn concentration: (a) for $x = 0$, (b) for $x = 0.1$ and (c) for $x = 0.2$.
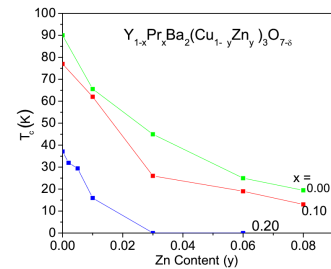
(i.e., $d\rho/dT$) of this linear part gives the carrier–carrier scattering. Figure 4 shows the behaviour of ρ_0 as function of y for only Zn and Zn plus Pr impurities. Figure 5 shows that $d\rho/dT$ for Zn and Zn plus Pr impurities. We analyse the data for $x = 0.1$ and $x = 0.2$ separately.

Figure 4a shows that for $x = 0.1$ Pr has a very small effect on ρ_0 and hence on pinning of charge stripes. For $x = 0.0$ Zn, $d\rho/dT$ in Fig. 5a, shows a rise up to $y = 0.03$ and then a fall, implying that there is no overall depinning effect which is seen in Fig. 3 which presents the T_c vs. y curve. T_c falls more or less uniformly as y increases. However when Pr is present, Fig. 5a shows that $d\rho/dT$ rises more sharply from $y = 0.02$ to $y = 0.06$. Then Fig. 4 shows that for this case T_c falls less rapidly with y in this region implying a depinning effect caused by Pr. The reason for this is that due to Pr substitution the holes start moving from their planar site to $4f$ band implying the starting of depinning of charge stripes.

For $x = 0.2$ the hole depletion process is in full swing and the system has made a transition to a new state. As shown in Fig. 3, T_c goes to zero at the Zn concentration

Fig. 3. Superconducting transition temperature T_c as a function of Zn content y for $Y_{1-x}Pr_xBa_2[Cu_{1-y}Zn_y]_3O_{7-\delta}$ samples with $x = 0$, 0.10, 0.20.

$y = 0.03$ and superconductivity is destroyed. Figure 4b shows that ρ_0 becomes large and Fig. 5b shows that $d\rho/dT$ becomes negative. This implies absence of depinning and a completely pinned charge stripe. It seems that the system has made a transition to underdoped stage and that just three percent of Zn has made ρ_0 large
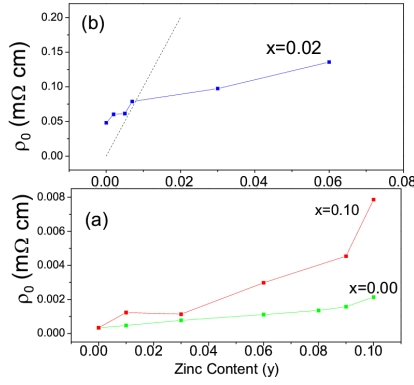
Fig. 4. Variation of residual resistivity ρ_0 as a function of Zn content y in $Y_{1-x}Pr_xBa_2[Cu_{1-y}Zn_y]_3O_{7-\delta}$ samples: (a) for $x = 0$, 0.10 and (b) for $x = 0.20$. The dotted line in (b) indicates the unitarity limit with the carrier density $n = 0.25$.
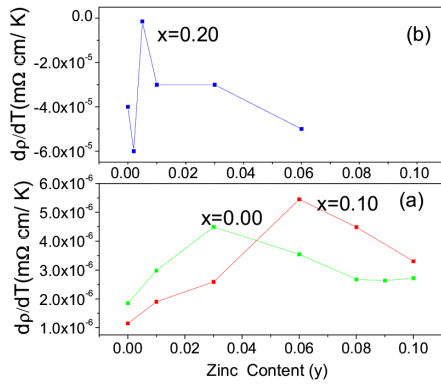

Fig. 5. Slope $d\rho/dT$ vs. zinc content y for different values of $Y_{1-x}Pr_xBa_2[Cu_{1-y}Zn_y]_3O_{7-\delta}$ samples: (a) for $x = 0$, 0.10 and (b) for $x = 0.20$.

enough to reach the unitarity value of $h/4e^2$ and induces superconductor to insulator transition.

In Fig. 4b we plot the unitarity line besides the ρ_0 vs. y curve using the relation 1 [16]:

$$\rho_0 = \frac{4\hbar}{e^2}\frac{n_i}{n}\sin^2\delta_0. \tag{1}$$

Here $\delta_0 = \pi/2$, $n_i = (3/2)y$. The value of n, the hole concentration per plane is taken to be 0.25 [16]. It is seen that ρ_0 comes close to the unitarity line till $y = 0.01$ when superconducting state exists.

4. Conclusion

We conclude that due to the hole depletion process Pr is able to bring the system in the underdoped region so that a small percentage of Zn is able to induce a superconductor–insulator transition. Such a situation has been observed earlier by Fukuzumi et al. [17] for Zn impurity alone by controlling the oxygen content in Y-123 system. We feel that it is easier to obtain the same results using Pr, since we can control the charge carrier density easily using the hole depletion mechanism.

References

[1] A.V. Narlikar, C.V. Rao, S.K. Agarwal, in: *Studies of High Temperature Superconductor*, Ed. A.V. Narlikar, Nova Science, New York 1989, Vol. 1, p. 341.

[2] M. Mehbod, P. Wyder, R. Deltour, P. Duvigneaud, G. Maessens, *Phys. Rev. B* **36**, 8819 (1987).

[3] J.M. Tarascon, P. Barboux, P.F. Miceli, L.H. Greene, G.W. Hull, M. Eibschutz, S.A. Sunshine, *Phys. Rev. B* **37**, 7458 (1988).

[4] G. Xiao, M.Z. Cieplak, A. Gavrin, F.H. Streitz, A. Bakhshai, C.L. Chien, *Phys. Rev. Lett.* **60**, 1446 (1988).

[5] Y. Xu, R.L. Sabatini, A.R. Moodenbaugh, Y. Zhu, S.G. Shyu, M. Suenaga, K.W. Dennis, R.W. McCallum, *Physica C* **169**, 205 (1990).

[6] H. Alloul, P. Mendels, H. Casalta, J.F. Marucco, J. Arabski, *Phys. Rev. Lett.* **67**, 3140 (1991).

[7] A.J. Millis, S. Sachdev, C.M. Varma, *Phys. Rev. B* **37**, 4975 (1988).

[8] R. Lal, *Phys. Rev. B* **51**, 640 (1995).

[9] G.V.M. Williams, J.L. Tallon, R. Meinhold, *Phys. Rev. B* **52**, R7034 (1995).

[10] G.D. Liu, Z.X. Zhao, G.C. Che, *Solid State Commun.* **109**, 495 (1999).

[11] J.S. Zhou, J.B. Goodenough, H. Sato, M. Naito, *Phys. Rev. B* **59**, 3827 (1999).

[12] Y. Yu, G. Cao, Z. Jiao, *Phys. Rev. B* **59**, 3845 (1999).

[13] R. Fehrenbacher, T.M. Rice, *Phys. Rev. Lett.* **70**, 3471 (1993).

[14] A.R. Gupta, R. Lal, A. Sedky, A.V. Narlikar, V.P.S. Awana, *Phys. Rev. B* **61**, 11752 (2000).

[15] C. Daniel, E. Marian, A. Terrell, *J. Chem. Educ.* **64**, 847 (1987).

[16] T.R. Chien, Z.Z. Wang, N.P. Ong, *Phys. Rev. Lett.* **67**, 2088 (1991).

[17] Y. Fukuzumi, K. Mizuhashi, K. Takenaka, S. Uchida, *Phys. Rev. Lett.* **76**, 684 (1996).