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LETTER

Normal and Anomalous Pseudogap of Superconducting $Y_{0.9-x}Pr_xCa_{0.1}Ba_2[Cu_{1-y}Zn_y]_3O_{7-\delta}$

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Abstract Electrical resistivity measurements on the superconducting oxides of the compositions $Y_{0.9-x}Pr_xCa_{0.1}Ba_2[Cu_{1-y}Zn_y]_3O_{7-\delta}$ ($0 \leq x \leq 0.20$ and $0.0 \leq y \leq 0.10$) sintered in oxygen atmosphere were carried out to obtain the normal and anomalous pseudogaps in underdoped and overdoped samples. It is observed that pseudogap temperature T^* decreases with increasing doping level p in the underdoped case. For the overdoped sample with $y = 0.06$, T^* shows no p dependence.

Keywords Superconducting oxides · Pseudogap · Resistivity

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1 Introduction

Normal pseudogap has been studied by Naquib et al. [1, 2] in Ca and Zn doped $YBa_2Cu_3O_{7-\delta}$ (Y123) compounds. The T^* is the characteristic temperature above which the resistivity curve takes the upturn. It has been established that [1, 2], T^* decreases linearly as the doping level p increases. This is a universal behavior observed in underdoped and optimally doped samples. It was later observed [3] that for Ca-based overdoped samples, an anomalous behavior of T^* appeared abruptly, showing very little or no p dependence.

In this paper we report our electrical resistivity measurements in under- and overdoped samples of Y123. For this purpose we use Pr substitution along with Ca. Pr substitutes at the Y site and is responsible for forming a narrow band called Fehrenbacher and Rice (FR) band near the Fermi energy [4]. This band grabs holes from the p–d band in the plane resulting in T_c reduction [5]. There are three regions in terms of Pr concentration x. For $0 < x < 0.1$ the system is in the vicinity of 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 the 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. For the underdoped region, we have used Pr content, $x = 0.1$ and 0.2, with various Zn contents and Ca content zero. For the overdoped region, we put Ca $= 0.1$ and x is varied for two values of Zn content, namely, 0.02 and 0.06. As shown in the results, these two combinations, i.e. of Pr and Ca, lead to the overdoped region. The doping level p is determined accurately using the room temperature (290 K) thermopower data.

2 Experimental Details

The polycrystalline samples with composition of $Y_{0.9-x}Pr_xCa_{0.1}Ba_2[Cu_{1-y}Zn_y]_3O_{7-\delta}$ with different values of x and y ($0 \leq x \leq 0.20$ and $0.0 \leq y \leq 0.10$) were prepared by solid-state reaction method. The ingredients, Y_2O_3, $CaCO_3$, $BaCO_3$, CuO, ZnO, Pr_6O_{11} of purity 99.99% in the stoichiometric ratio, were thoroughly mixed, grounded and calcined at 920 °C in air for a period of 20–24 h. After four intermediate grindings and calcinations in air the precursors so obtained were reground and pressed into 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 [6]. The samples were then characterized by X-ray diffraction (XRD) using a Rigaku X-ray diffractometer with CuK_α

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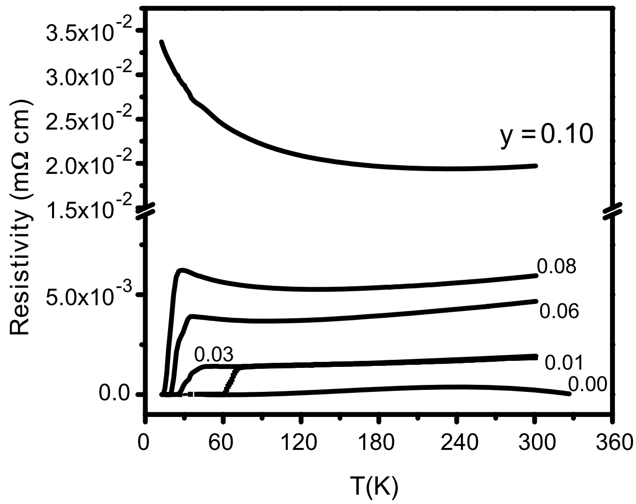

Fig. 1 Resistivity vs. temperature plots for $Y_{1-x}Pr_xBa_2[Cu_{1-y}Zn_y]_3O_{7-\delta}$ samples with $x = 0.10$ and different values of Zn concentration (y)

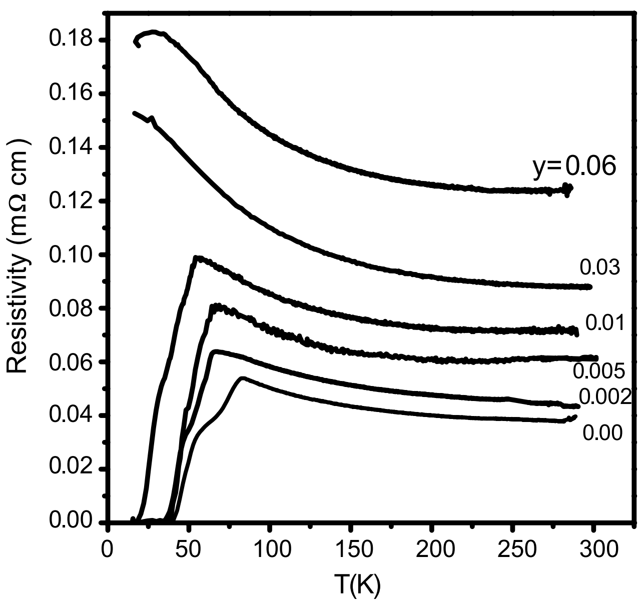

Fig. 2 Resistivity vs. temperature plots for $Y_{1-x}Pr_xBa_2[Cu_{1-y}Zn_y]_3O_{7-\delta}$ samples with $x = 0.20$ and different values of Zn concentration (y)

radiation, and the phase purity of the samples was checked using Rietveld Analysis Program DBWS-9411. The structure for all the samples of the series is found to be orthorhombic. The electrical resistivity was measured using standard four-probe method employing silver point contact in the temperature range of 14–300 K using a close cycle refrigerator for temperature variation, as shown in Figs. 1, 2, 3 and 4. The oxygen content of the samples was determined by iodometric titration [7] which is found to be 6.7 ± 0.1. The thermopower measurements were carried out at room temperature (290 K) in our laboratory.

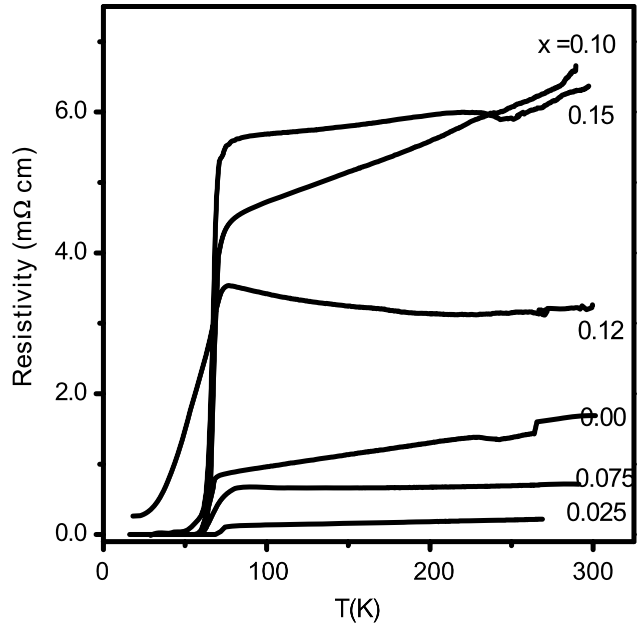

Fig. 3 Resistivity vs. temperature plots of $Y_{0.9-x}Pr_xCa_{0.1}Ba_2(Cu_{1-y}Zn_y)_3O_{7-\delta}$, with $y = 0.02$ and different values of Pr concentration (x)

Table 1 Experimental data on T_c, T^* and p for the underdoped system $Y_{1-x}Pr_xBa_2(Cu_{1-y}Zn_y)_3O_{7-\delta}$ for different values of Zn and $x = 0.1, 0.2$

Concentration of Zn (y)	T_c (K)	T^*	p
(a) $x = 0.1$			
0.00	77	253.52	0.12071
0.01	62	251.85	0.12685
0.03	26	247.40	0.1411
0.06	19	244.29	0.15178
0.08	13	240.73	0.16278
0.10	–	238.18	0.16991
(b) $x = 0.2$			
0.00	37.08	256.3	0.1068
0.002	31.99	254.86	0.11462
0.005	29.4	249.85	0.13107
0.01	15.96	245.73	0.14627
0.03	–	239.77	0.16666
0.06	–	236.06	0.17508

3 Results and Discussion

Figures 1 and 2 represent the resistivity (ρ) vs. T plots for underdoped samples and Figs. 3 and 4 represent resistivity vs. temperature plots for overdoped samples. In Fig. 4(b) we show the ρ vs. T curve taken from Ref. [3] (Naquib et al.) for comparison. We find that the trend in curves 4(a) and 4(b) is almost similar suggesting thereby the constancy of hole concentration. Following Naquib et al. [1] we have

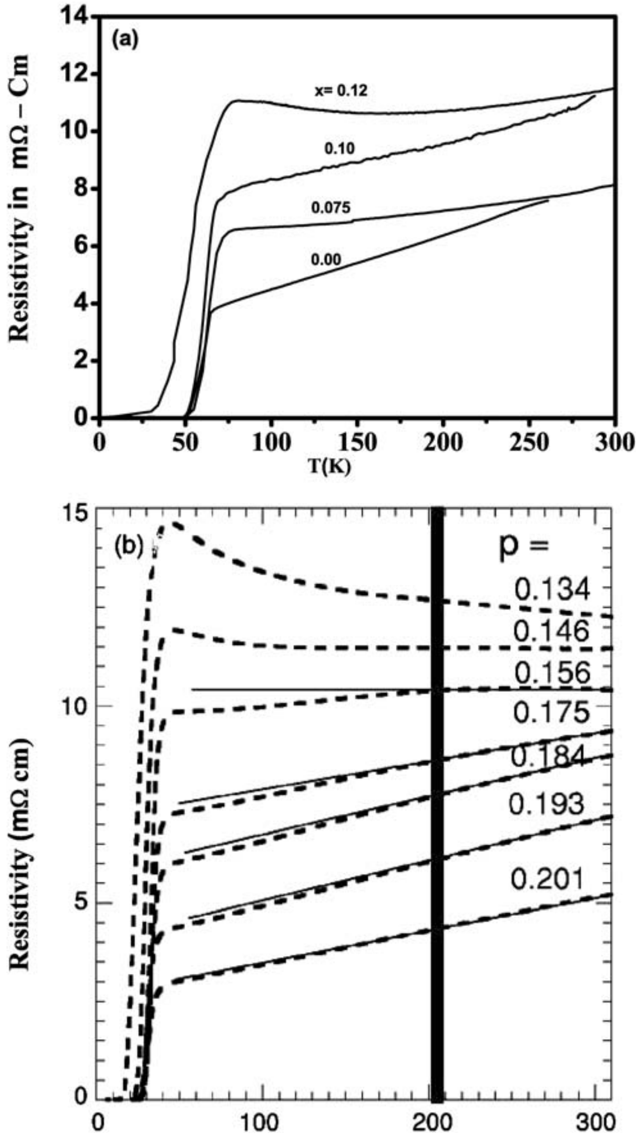

Fig. 4 (**a**) Resistivity–temperature curves for $Y_{0.9-x}Pr_xCa_{0.1}Ba_2(Cu_{1-y}Zn_y)_3O_{7-\delta}$ with $y = 0.06$ and different values of Pr content (x). (**b**) Resistivity–temperature curves for sintered $Y_{0.80}Ca_{0.20}Ba_2(Cu_{0.945}Zn_{0.55})_3O_{7-\delta}$ samples, after each oxygen annealing from Ref. [3] shown for comparison

determined T^* from ρ–T at which upturn appears. The hole concentration, p, is obtained from the room temperature thermopower data. Plots of T^* vs. p for the underdoped and overdoped samples are given in Figs. 5 and 6. For the underdoped case at $x = 0.1$ and $x = 0.2$ the system is in the hole depletion region, and p is varied by increasing Zn concentration as shown in Table 1. Here it may be noted that Zn acts as pinning the holes in the plane and opposes the action of Pr in removing the holes. Consequently, p increases as Zn concentration increases, as can be seen from Fig. 5 (a) and (b). Zn is known to suppress T_c faster [8]. The resistivity measurements on the underdoped samples show normal pseudogap behavior, i.e. T^* decreases linearly with increasing p (see Fig. 5 (a), (b)). For the overdoped case we have set $y = 0.02$ and $y = 0.06$, and x is varied and the measurements are summarized in Table 2, and the T^*–p curves are shown in Fig. 6 (a) and (b). For $y = 0.02$ concentration, T^* shows normal behavior. However, at $y = 0.06$ concentration, T^* remains almost constant and is independent

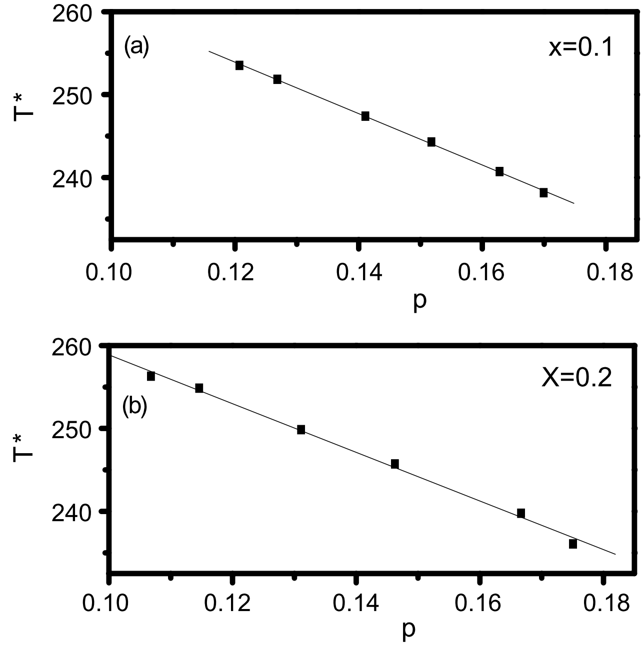

Fig. 5 Plots of T^* against p for $Y_{1-x}Pr_xBa_2(Cu_{1-y}Zn_y)_3O_{7-\delta}$ samples for $x = 0.1$ (**a**), and $x = 0.2$ (**b**), for y varying from 0.00 to 0.10

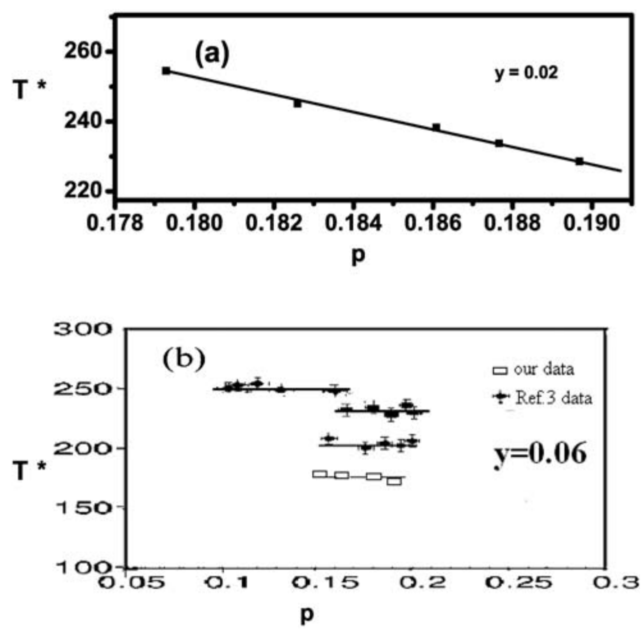

Fig. 6 Plots of T^* against p for $Y_{0.9-x}Pr_xCa_{0.1}Ba_2(Cu_{1-y}Zn_y)_3O_{7-\delta}$ samples for $y = 0.02$ (**a**), and $y = 0.06$ (**b**), for x varying from 0.00 to 0.15. Here in (**b**) the data from Naquib et al. (Ref. [3]) is reproduced for comparison

Table 2 Experimental data on T_c, T^* and p for $Y_{0.9-x}Pr_xCa_{0.1}Ba_2(Cu_{1-y}Zn_y)_3O_{7-\delta}$ with $y = 0.02$, 0.06 and different values of x

Concentration of Pr (x)	T_c (K)	T^*	p
(a) $y = 0.02$			
0	57.9	254.56	0.17928
0.025	67.43	245.13	0.18259
0.075	58.67	238.33	0.18608
0.1	49.45	233.79	0.18766
0.12	22.66	228.58	0.18968
(b) $y = 0.06$			
0	46.05	242.92	0.1799
0.075	55.43	243.73	0.18136
0.1	44.66	242.63	0.18456
0.12	20.79	21.54	0.18682

of p. This is the anomalous pseudogap. Just for comparison we have shown results from Naquib et al. (Ref. [3]) in Fig. 6(b), which agree well with our results. These authors showed that the anomalous behavior appears for $y \geq 0.05$. Our results thus corroborate the earlier results obtained by Naquib et al. [3] and hence the theoretical explanation given by these researchers [3] can still hold good.

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