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Hole Concentration in $GdBaSrCu_{3-x}Zn_xO_{7-\delta}$ System: Interplay among Superconductivity, Stripe Order and Pseudogap

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Abstract

Polycrystalline $GdBaSrCu_3O_{7-\delta}$ samples with Zn substitution were prepared via solid state reaction. The superconducting properties of Zn substituted $GdBaSrCu_3O_{7-\delta}$ samples have been studied by X-ray diffraction, resistivity, AC susceptibility and oxygen content measurements. Hole concentration of these samples was determined according to the oxygen content measured by iodometric titration method. Zn substitution doesn't change the tetragonal structure of the sample but reduces both T_c and hole concentration, which is attributed to hole filling by Zn. The non-magnetic Zn^{2+} substitution have significant effects on the oxygen content and effective Cu valence of these *d*-wave superconductors. The correlation between calculated hole concentration from oxygen content data and T_c obtained leads to the possibly interplay among the superconducting and stripe correlations in $GdBaSrCu_{3-x}Zn_xO_{7-\delta}$ samples.

Keywords

Hole concentration, non-magnetic impurity, transition temperature.

Introduction

Superconductivity is believed to occur in the Cu(2)-O_2 sheets through hole charge carriers, and the oxygen content of Cu(1)-O chains governs the hole carries concentration in the Cu(2)-O_2 sheets. However, consent on the transition from parent Mott antiferromagnetic (AFM) insulator to

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superconducting still remains unclear. Cuprates exhibit various correlations in both normal and superconducting state as the holes, p, or charge carriers is varied. The relevance of charge/spin stripe order (Tallon et al., 2001; Damascelli et al., 2003; Emery et al., 1995) on superconductivity is one of the most extensively studied phenomena.

Pseudogap extrapolated from T-p phase diagram over a wide range of hole content leads to a number of non-Fermi-liquid like features in both normal and superconducting states. Based on the pairing scenario, Pseudogap arises from strong fluctuations of superconducting origin in the strong coupling regime for systems with low dimensionally (high structural and physical anisotropy) and low superfluid density (Emery et al., 1995). On the other hand, pseudogap is attributed to some other correlations of non-superconducting origin (Tallon et al., 2001).

It is well established that the static spin/charge stripe correlations are observed in underdoped cuprates in the vicinity of $p \sim 0.125$ (so-called 1/8th anomaly) (Tranquada et al., 1995; Berg et al., 2009) and the dynamical (fluctuating) stripe correlations are believed to exist over a much wider doping range, especially in the single CuO_2 layer La214 compounds (Berg et al., 2009; Kivelson et al., 2003). Therefore, it is believed that stripe ordering is a generic feature of hole doped cuprate superconductors.

Previous studies on Zn doped $YBa_2Cu_3O_7$ superconductors showed Zn atoms mainly take the Cu(2) sites in the CuO_2 planes and such substitution may be useful in understanding the mechanism of superconductivity in these materials (Takayama-Muromachi et al., 1987; Tallon et al., 1997). Zn^{2+} as a non-magnetic ion, disrupts the local antiferromagnetic correlation of Cu(2) spin and thereby induces a localized paramagnetic moment shared by four neighbouring Cu(2) sites (Mahajan et al., 1994; Alloul et al., 1997). Since the ionic size and orbital structure of 3*d* elements are closed to those of Cu, 3*d* elements will occupy the Cu sites if they are substituted into Cu-based high temperature superconductors. On the other hand, such doping decreased the oxygen content and the structure gradually undergoes an orthorhombic-to-tetragonal transition.

A series of $GdBaSrCu_{3-x}Zn_xO_{7-\delta}$ bulk samples ($0 \le x \le 0.1$) were prepared via solid-state reaction. The non-magnetic Zn^{2+} substitution should have significant effects on the oxygen content and effective Cu valence of these *d*-wave superconductors. All samples were prepared under the same condition and hence, any significant variation of the result might not be due to the samples' preparation.

Methodology

$GdBaSrCu_{3-x}Zn_xO_{7-\delta}$ (x = 0, 0.01, 0.04, 0.07 and 0.10) polycrystalline samples were prepared by mixing appropriate amounts of high purity (≥ 99.99 %) Gd_2O_3, $BaCO_3$, $SrCO_3$, CuO and ZnO powders. The mixed powders were calcined in air at around 950 ^oC for 48 h with several intermittent grindings and furnace cooled. The powders were then pressed into pellets. The pellets were sintered at 950 ^oC for another 24 h and furnace cooled. The samples were then annealed in flowing O_2 at 950 ^oC for more than 10 hours to increase the oxygen content.

The phase of these samples was examined by X-ray powder diffraction with CuK$_\alpha$ radiation using a RINT2000 Wilder-angle goniometer. Four-point probe was used to measure the resistivity of the samples at room temperature. Magnetization measurement was carried out to determine the superconducting behavior (if any) of these samples. Oxygen content of the samples was carried out by iodometric titration method, and subsequently the Cu valance was determined.

Results and Discussion

Powder X-ray diffraction patterns show all samples to be single-phased with tetragonal structure (space group *P4*/*mmm*). This convinces that Zn is substituted completely in these samples. The lattice parameters are calculated as shown in Table 1. There is no systematic correlation being observed between doping content (*x*, for both dopants) and lattice parameters. Such substitution does not change the lattice or the structure of these samples. Hence, any phenomenon that may occur in this study is assumed to be irrelevant to the structure change among the samples. On the other hand, it may disrupt the intrinsic properties of these samples.

Table 1. Oxygen content, hole concentration (p), critical temperature ($T_{c\ onset}$ and $T_{c\ zero}$) and lattice parameter (a=b, c) of GdBaSr(Cu$_{3-x}$Zn$_x$)O$_{7-\delta}$ samples.

Doped content (x)	Oxygen content	Hole concentration (p)	$T_{c\ onset}$ (K)	$T_{c\ zero}$ (K)	Lattice parameter	
					a (Å) = b (Å)	c (Å)
0.00	6.9371	0.2914	83 ± 1	70 ± 1	3.854 ± 0.004	11.571 ± 0.007
0.01	6.9358	0.2915	77 ± 1	55 ± 1	3.837 ± 0.003	11.550 ± 0.006
0.04	6.8775	0.2551	75 ± 1	53 ± 1	3.847 ± 0.003	11.545 ± 0.005
0.07	6.8453	0.2357	66 ± 1	45 ± 1	3.837 ± 0.003	11.517 ± 0.005
0.10	6.6317	0.0908	-	-	3.846 ± 0.003	11.542 ± 0.005

The temperature dependent of normalized electrical resistance of these polycrystalline samples is shown in Figure 1. Results show that both Zn doping suppresses the T_c as listed in Table 1. Such behavior was confirmed through the magnetization measurement (Figure 2). Superconductivity is destroyed for 10% (x = 0.1) of Zn doped sample down to 20 K of observation.

The values of oxygen content and hole concentration (p) determined by the iodometric titration method are listed in Table 1. Results reveal both oxygen content and hole concentration decrease with increasing Zn content in the samples. However, results don't reveal the 1/8th anomaly as usually observed in orthorhombic cuprate high-T_c superconductors. This could be due to the occupancy of oxygen atoms in tetragonal structure of these samples is less compare to those samples in orthorhombic structure such like YBCO.

Figure 1. Normalized electrical resistance versus temperature of $\mathrm{GdBaSrCu_3O_{7-\delta}}$ (Gd00), $\mathrm{GdBaSrCu_{2.99}Zn_{0.01}O_{7-\delta}}$ (GdZn01), $\mathrm{GdBaSrCu_{2.96}Zn_{0.04}O_{7-\delta}}$ (GdZn04), $\mathrm{GdBaSrCu_{2.93}Zn_{0.07}O_{7-\delta}}$ (GdZn07) and $\mathrm{GdBaSrCu_{2.90}Zn_{0.10}O_{7-\delta}}$ (GdZn10) samples.

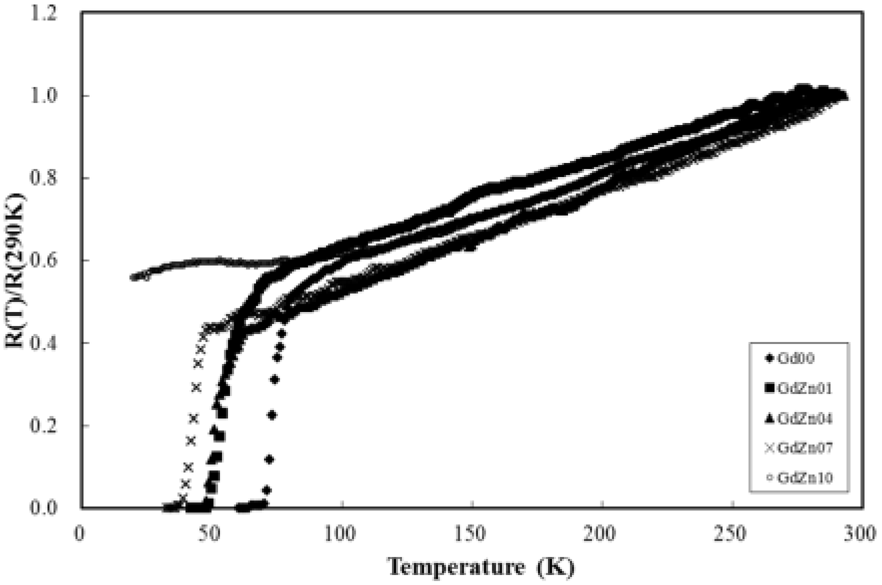
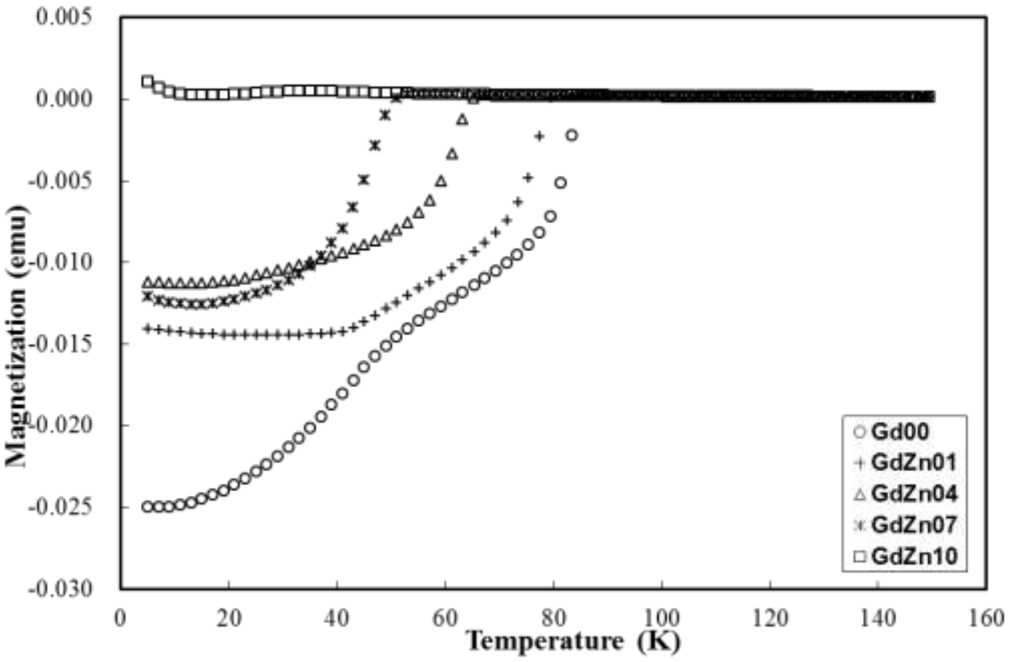


Figure 2. Temperature dependent of magnetization for $\mathrm{GdBaSrCu_3O_{7-\delta}}$ (Gd00), $\mathrm{GdBaSrCu_{2.99}Zn_{0.01}O_{7-\delta}}$ (GdZn01), $\mathrm{GdBaSrCu_{2.96}Zn_{0.04}O_{7-\delta}}$ (GdZn04), $\mathrm{GdBaSrCu_{2.93}Zn_{0.07}O_{7-\delta}}$ (GdZn07) and $\mathrm{GdBaSrCu_{2.90}Zn_{0.10}O_{7-\delta}}$ (GdZn10) samples.



The strongly p-dependent rate of suppression of T_c for the various cuprates can be explained assuming strong potential (unitary) scattering by non-magnetic Zn in the presence of a $d_{x^2-y^2}$ order parameter and evidence of such strong pair-breaking scattering is found from the STM study (Pan et al., 2000). Decreasing of T_c is related to the disruption of spin correlation of the antiferromagnetic CuO_2 planes and Zn doping as a non-magnetic dopant might induce more unpaired hole carriers. Previous report (Hao et al., 1994) showed that Zn doping decreased the O *p* holes and increased the Cu *d* holes locally which is disadvantageous for superconductivity. On the other hand, Zn is believed to pin the fluctuating stripe order (Akoshima et al., 2000; Risdiana et al., 2008). The pinning mechanism can be attributed to Zn-induced enhancement of the AFM correlations, carrier localization or to the increase in the stripe inertia.

Figure 3. Dependence of T_c on doped content (x) for $GdBaSr(Cu_{3-x}Zn_x)O_{7-\delta}$ with x = 0.00, 0.01, 0.04, 0.07 and 0.10.

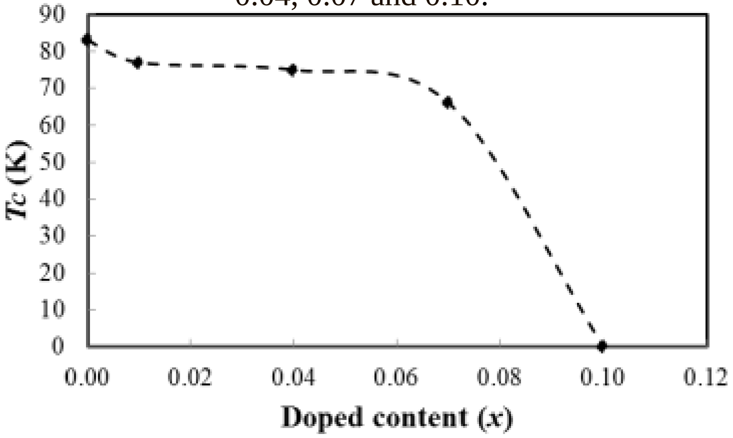
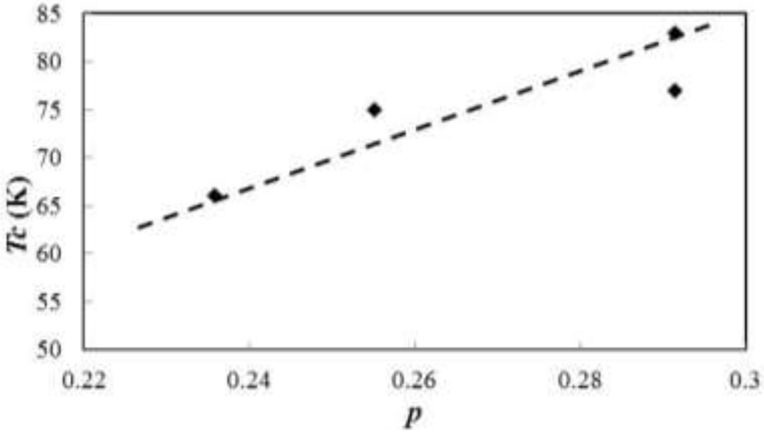


Figure 4. T_c versus hole concentration (p) for $GdBaSr(Cu_{3-x}Zn_x)O_{7-\delta}$ with x = 0.00, 0.01, 0.04, 0.07 and 0.10.



As conclusions, we reported the effect of Zn on T_c as a function of hole concentration for $GdBaSrCu_{3-x}Zn_xO_{7-\delta}$ bulk samples. The hole concentration can be varied by varying Zn doping content without changing the tetragonal structure of the $GdBaSrCu_3O_{7-\delta}$ samples. Hole concentration p decreases as Cu^{2+} is substituted by Zn^{2+}. There is a correlation between hole concentration p and critical temperature T_c whereby p decreases as Cu^{2+} is substituted by Zn^{2+}.

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