DEPENDENCE OF TRANSITION TEMPERATURE ON HOLE CONCENTRATION PER CuO$_2$ SHEET IN THE BI-BASED SUPERCONDUCTORS

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Abstract

The recently observed variations of the transition temperature $T_c$ with oxygen content in the Bi-based (2212) and (2223) superconductors are analyzed in terms of $p^+$, the hole concentration per CuO$_2$ sheet. This analysis shows that in this systems $T_c$ increases with $p^+$ initially, reaching maxima at $p^+= 0.2 \sim 0.3$, followed by monotonic decrease of $T_c$ with $p^+$. The forms of these variations are similar to those observed in the La$_{2-x}$Sr$_x$CuO$_4$ and YBa$_2$Cu$_3$O$_y$ systems, suggesting that $p^+$ may be an important variable governing superconductivity in the cuprate superconductors.

Among the cuprate high-$T_c$ superconductors, La$_{2-x}$Sr$_x$CuO$_{4-\delta}$ is a prototype since the unit cell of this system contains only a single CuO$_2$ sheet [1]. The hole concentration or excess valence $p^+$ on the CuO$_2$ sheet in an ionic charge lattice represented by La$_{2-x}$Sr$_x$CuO$_{4-\delta}$ is given by $p^+ = x - 2\delta$, meaning that $p^+$ can be varied by varying either $x$ or $\delta$ [2,3]. With $\delta = 0$, $T_c$ increases from 0 to 38 K as $x$ increases from 0.06 to 0.15, $T_c$ starts to decrease for $x > 0.15$ and superconductivity disappears for $x > 0.27$ [2,3]. This result indicates the existence of two superconducting states: a hole (carrier)-deficient state and hole (carrier)-excess state. For the hole-deficient state, $T_c$ increases with holes concentration whereas for the hole-excess state, $T_c$ decreases as the hole concentration increases.

For the (123) family of superconductors represented by YBa$_2$Cu$_3$O$_y$ [4], superconductivity vanishes for stoichiometric composition $y = 6.5$ and for $y > 6.5$, $T_c$ increases with $y$, reaching 93 K for $y \sim 7.0$. In this system, each unit cell contains two CuO$_2$ sheets and a CuO chain. The question of where the excess holes resides leading to superconductivity has been studied by Tokura et al [5]. According to their analysis, the excess holes $p$ given by $p = (2y - Q - 6)/3$ is distributed as $p_{sh} = (y - 6.5)/2$, and $p_{ch} = (y - 6.5)$ with $p = (2p_{sh} + p_{ch})/3$. In the above, $Q$ is the total cationic charge (excluding Cu), and $p_{sh}$ and $p_{ch}$ respectively represent the excess holes in the CuO$_2$ sheets and CuO chain. They further suggested that holes associated with chains, $p_{ch}$, are localized and merely provide an insulating reservoir of charge whereas $p_{sh}$ is the principal variable governing superconductivity. If $p^+$ represents hole concentration per CuO$_2$ sheet, then $p^+ = p_{sh}/2$ for the (123) system. By doping with La and Ca,
Tokura et al. showed that $T_c$ initially increases with $p^+$ for $p^+ > 0$, reaches maximum of $T_c \approx 85$ K at around $p^+ = 0.2$ and for $p^+ > 0.2$, a decrease of $T_c$ is seen.

The idealized structure of the $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_{8+\delta}$ (2212) superconductor is quite similar to that of the (123) compound with Ca, SrO and double BiO layers replacing Y, BaO and CuO chain layers respectively. $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ (2223) phase can be formed by inserting one more (CuO$_2$ + Ca) slab into the (2212) phase. From the structure similarities, one may expect that excess oxygen atoms are residing in the double BiO layer, playing the same role as the excess oxygen in the CuO chains for the (123) superconductor. However, the situation for the Bi (2212) phase is complicated. First of all, the exact location of the excess oxygen atoms in the compound is still unclear. Secondly, there are numerous deviations from the idealized structure and composition in the Bi and Tl superconductor systems, especially in the double Bi(Tl)O layers and the Sr(Ba)O layers. Deviations such as strontium deficiency [6] (Sr:Ca < 2:1 for the (2212) phase) also creates holes on the CuO$_2$ sheets. Attempt to vary the oxygen content will inevitably alter the structure to some extent. Thirdly, on synthesizing the high $T_c$ (2223) phase, intergrowth with a low $T_c$ phase often occurs in this system which makes quantitative study on a single phase difficult.

A number of studies [7-11] have shown that $T_c$ in the Bi superconductors is sensitive to oxygen stoichiometry. For example, Morris et al [9] observed increase in $T_c$ with the decrease of oxygen content for the (2212) phase. They varied oxygen content by annealing the samples at different oxygen pressures [9]. We used a TGA (Thermogravimetric Analysis) apparatus to heat a $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_{8+\delta}$ (2212) sample to < 850°C and subsequently quench the samples in Ar gas [10]. This method is relatively simple. Since the sample treatment was carried out at atmosphere pressure, it is less destructive than other methods and the weight variation can be monitored in situ with 1 $\mu$g sensitivity. By varying the quenching temperature, we were able to affect the oxygen content by different levels and we observed an increase of $T_c$ of 25 K as a result of loss of 0.09 oxygens per formula unit. By the same technique, we studied a Pb-doped Bi superconductor consisting of the (2223) phase with an admixture of the (2212) phase [11]. Here we observed that with loss of oxygen, $T_c$ of the (2212) phase increased from 70 K to 90 K, whereas that of the (2223) phase decreased from 107 to 90 K. These results suggested that the as-prepared Bi (2212) phase is in the hole-excess state whereas the Bi (2223) phase is in the hole-deficient state. For an as-prepared Tl (2223) phase sample, $T_c$ has been observed to decrease with decrease of oxygen content [12,13] whereas for an as-prepared Tl (2201) phase sample [14], $T_c$ increases with decrease of oxygen content.

At first glance, the above findings on the variation of $T_c$ with hole concentration in the (2212) and (2223) phases of the Bi superconductors do not fit into a consistent picture. Furthermore, the $T_c$'s of the Bi (2201), (2212), (2223) and (2234) phases are quite different viz. 10, 85, 110 and 90 K respectively and these results need to be understood. Here we show that when the observed findings of the variation of $T_c$ with oxygen content in the Bi superconductor are analyzed in terms of $p^+$, the hole concentration per CuO$_2$ sheet, a consistent picture emerges. In addition, the variation of $T_c$ with $p^+$ in
Bi and possibly in Tl superconductors is quite similar to that shown in the La$_{2-x}$Sr$_x$CuO$_{4-\delta}$ and the YBa$_2$Cu$_3$O$_y$ superconductors, providing a consistent picture for the four families of the cuprate superconductors.

The Bi (2223)+(2212) phase sample we prepared is not a simple mixture of two compounds. As mentioned in the previous paragraph, during the formation of the (2223) phase, intergrowth of the (2212) phase occurs. Therefore the double Bi-O layers are often shared by the (2212) and the (2223) phases. If we assume that excess oxygen atoms are residing in the double BiO layers, the amount of the holes provided by the excess oxygen atoms will be shared by two CuO$_2$ sheets in the (2212) phase case and by three CuO$_2$ sheets in the (2223) phase case. According to literature [15,16], $\delta$ in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ varies from 0.15 to 0.6 for the as-prepared (2212) phase sample. With the consideration of the holes created by strontium deficiency [6], we assume there is 0.8 holes per formula unit. Then in average, the hole concentration per sheet, $p^+$, is given by $p^+ = 0.8/n$. This gives $p^+ = 0.4$ and 0.27 for the (2212) and (2223) phases respectively. Using these two values for the as-prepared samples, the variations of $T_c$ with $p^+$ for the (2212) and (2223) phases based on our data [10,11] are shown in Fig. 1. A different choice of $\delta$ shifts $p^+$ at which the maximum $T_c$ is observed. However general shape of the curve remains the same. Fig. 1 shows that the as-prepared Bi (2223) is in a carrier-deficient state whereas the as-prepared Bi (2212) phase is in a carrier-excess state. This explains the opposite directions of the $T_c$ variation observed in the (2223) and (2212) phases as a result of loss of oxygen [7-11]. According to the above scheme, one may explain that $T_c$ for the (2234) phase with four CuO$_2$ sheets is lower (90 K) than that for the (2223) phase because of the smaller $p^+$ value and the low $T_c$ (~ 10 K) for the (2201) phase with one CuO$_2$ sheet because of the larger $p^+$ value. In addition, the as-prepared Bi (2234) and (2201) phase samples are expected to belong to carrier-deficient and carrier-excess states respectively if the structure of the double BiO layer and the SrO layers remains the same as that for the (2212) and (2223) phases. We note that Urland and Tietz [15] have reported the variation of $T_c$ with $p^+$ for the Bi (2212) phase. $T_c$ variation was achieved by varying Sr:Ca ratio and oxygen content. They showed that as $p^+$ increases from 0.1 to 0.6, $T_c$ first increases from 73 to 80 K, remaining at 80 K for $p^+ = 0.2 \sim 0.4$, then falling for $p^+ > 0.4$. Their results suggest that for a single Bi or Tl phase, the variation of $T_c$ with $p^+$ may follow the same shape as that in Fig. 1. Recently, similar results have been reported by Yoshizaki et al [17] and Torrance et al [18] respectively in Y doped, and Na and K doped Bi (2212) samples. Maximum $T_c$'s were found at $p^+ = 0.15 \sim 0.25$. In the case of La doped (2201) Bi$_2$Sr$_{2-x}$La$_x$CuO$_{6+\delta}$ compound [19], Groen et al showed that the as-prepared (2201) phase is in a carrier-excess state. Maximum $T_c = 28$ K was observed at $p^+ = 0.3$ and for $p^+ < 0.21$, the sample became non-superconductor.

In the above, we have shown that the variation of $T_c$ with $p^+$ for the Bi (2212) and (2223) phases may be represented by Fig. 1. Moreover the shape of the curve in Fig. 1 is similar to that for the (123) [5] and La$_{2-x}$Sr$_x$CuO$_{4+\delta}$ [2,3] superconductors although the magnitude of $p^+$ corresponding to the maximum $T_c$ is somewhat different for different families of superconductors. According
to previous experimental results [12,13,14], it is likely that the variation of $T_c$ with $p^+$ for the Tl-based superconducting phases may follow a pattern similar to that in Fig. 1 with maximum $T_c = 125$ K. These results suggest that $p^+$ (excess valence per CuO$_2$ sheet) may be an important variable for the cuprate superconductors and these results should form the major test for any successful theory of superconductivity.

It is interesting to note that without the hole reservoir, $T_c$ for La$_{2-x}$Sr$_x$CuO$_{4.8}$ is below 40 K. With CuO chain, double BiO layers and double TlO layers as hole reservoirs, $T_c$ increases to 93 K, 110 K and 125 K respectively. It appears that the key to the differences in $T_c$ is the interaction between the hole reservoir part and the CuO$_2$ sheets. Bishop et al [20] argued that although superconductivity itself takes place on the CuO$_2$ sheets, the attractive pairing mechanism is not two-dimensional but may require dynamic coupling of these sheets to the surrounding polarizable environment in order to understand the difference in the $T_c$'s of the four families of superconductors.

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REFERENCES


Fig. 1. The variations of $T_c$'s with $p^+$ for the Bi (2212) and (2223) phases.