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Study of doping effects on transition temperature of La_{2-x} $(Ca, Na, K)_xCuO_4$ superconductors

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Abstract. We have investigated doping effects on the transition temperature (T_c) of $La_{2-x}M_xCuO_4$(M = Ca, Na and K) by incorporating the effects of two-dimensional (2D) acoustic plasmons in the framework of the strong coupling theory. The contributions from 2D acoustic plasmon mechanism to T_c have been obtained from a Fourier-transformed effective potential, which has been earlier found to be successful in predicting the composition dependence of T_c in $La_{2-x}(Ba, Sr)_xCuO_4$. The results obtained by us on the variation of transition temperature with composition (x) in $La_{2-x}M_xCuO_4$ superconductors are in reasonably good agreement with the available experimental data. This success has led to the conclusion that 2D acoustic plasmons are adequate to explain the pairing mechanism and the variation of T_c with composition (x) in cuprate superconductors.

Keywords. Pairing mechanism; 2D acoustic plasmons; coupling parameter; Coulomb repulsion; transition temperature; Fourier-transformed effective potential.

1. Introduction

Recently, high-temperature superconductors (HTSCs) have attracted considerable attention because of their primary importance in both fundamental research and technological applications. We have investigated the effects of the two-dimensional (2D) acoustic plasmons and succeeded in revealing the composition dependence of the transition temperature (T_c) in $La_{2-x}(Ba/Sr)_xCuO_4$ (Singh *et al* 1993) using the Fourier-transformed effective potential (FTEP) approach. The transition temperatures of these superconductors lie in the range 30–40 K. Besides these, there are other members of the lanthanum cuprate family, viz. $La_{2-x}Ca_xCuO_4$ (Bednorz and Muller 1986; Bednorz *et al* 1987), $La_{2-x}Na_xCuO_4$ (Markert *et al* 1988) and $La_{2-x}K_xCuO_4$ (Subramaniam *et al* 1988) with T_c around 20 K.

Motivated by the success of our earlier FTEP approach and the availability of some experimental data, we thought it pertinent, probably for the first time, to predict the composition (x) dependence of T_c in $La_{2-x}(Ca, Na, K)_xCuO_4$. Thus, the main aim of the present paper is to employ the FTEP approach (Singh *et al* 1993) to analyse the composition dependence of T_c in these superconductors. We have achieved considerable success in predicting the observed composition (x) dependence of T_c in Ca, Na and K-doped La_2CuO_4 superconductors with $T_c = 18$ K ($x = 0{\cdot}15$), 16 K (18 K) ($x = 0{\cdot}11$ ($= 0{\cdot}41$)) and 19 K ($x = 0{\cdot}71$), respectively. The essential formalism of FTEP is given in § 2. The computed results and their discussions are presented in § 3.

2. Essential formalism

Earlier, we have demonstrated that 2D acoustic plasmons play a significant role in providing a plausible explanation of the pairing mechanism and the superconducting state properties of $La_{2-x}(Ba, Sr)_xCuO_4$ using the following Fourier-transformed effective potential approach (Singh *et al* 1993):

$$V_{\rm eff}(q, q_z, \omega) = \frac{2\pi e^2 d}{\varepsilon_\infty} R(q, q_z, \omega), \tag{1}$$

with the terms having the same meaning as described in our earlier paper.

Using this potential, we have derived the following expressions for the averaged Coulomb repulsive parameter (μ) and the coupling parameter (λ) as

$$\lambda = \frac{\pi[1 - ((1+\omega_c)/2)(1-\omega_c)^{1/2}]}{(3 + \Omega_1^2 a^* m^* d/12\varepsilon_\infty E_f)(1 - \cos\theta_c)}, \tag{2}$$

$$\mu = \frac{2\pi e^2 d}{\varepsilon_\infty} \mu(0) \ln\left[\frac{2+D}{D}\right]. \tag{3}$$

The various terms in them have the same meaning as defined in our earlier paper (Singh *et al* 1993).

The cut-off plasmon frequency (ω_c) for which the effective potential remains attractive is obtained as (Singh *et al* 1993)

$$\omega_c = 1{\cdot}4[(n_c B)^{1/2} - 0{\cdot}28 m^* B]. \tag{4}$$

The modified Coulomb repulsion parameter (μ^*) is expressed as (Ruvalds 1987)

$$\mu^* = \frac{\mu}{1 + \mu \ln(E_f/\omega_c)}, \tag{5}$$

in terms of μ, ω_c and Fermi energy (E_f). We have evaluated the transition temperatures (T_c) from the relation (Ruvalds 1987)

$$T_c = 0{\cdot}7\omega_c \exp\left[\frac{1+\lambda}{\lambda - \mu^*}\right], \tag{6}$$

for different compositions (x). The results thus obtained have been discussed below.

3. Results and discussion

We have computed the values of the model parameters λ, μ^* and ω_c at different compositions (x) using the expressions given by (2)–(5) for $La_{2-x}M_xCuO_4$(M = Ca, Na and K) in the ranges $0{\cdot}0 \leqslant x \leqslant 0{\cdot}30$, $0{\cdot}0 \leqslant x \leqslant 0{\cdot}60$ and $0{\cdot}0 \leqslant x \leqslant 0{\cdot}71$. For this purpose, we have used the value of $\varepsilon_\infty = 4{\cdot}5$ which is the same as reported by Bozovic (1990) for Ba and Sr substitutions in $La_{2-x}M_xCuO_4$(M = Ba, Sr). The values of effective mass (m^*) are taken to be $4m_e$, $3m_e$ and $2m_e$ for Ca, Na and K dopings on the basis of the same reasonable grounds as taken to be 6 and $5m_e$ in the cases of Ba- and Sr-doped cuprates.

We have made the model parameters dependent on composition (x) through the 2D charge carrier density, n_c expressed as $n_o \times 10^{14}\,cm^{-2}$ with n_o varying from 0·0 to 1·2, 0·0 to 1·0 and 0·0 to 0·7 respectively for Ca-, Na- and K-doped superconductors. These values have been expressed as a function of composition (x) on the basis of their values reported by Ong *et al* (1987) from Hall effect measurements for Ba and Sr-doped superconductors. Although these values for $La_{2-x}M_xCuO_4$ (M = Ca, Na, K) have not been measured so far, they are consistent with the values determined by Ong *et al* (1987).

The values of the model parameters, particularly λ and ω_c, have been obtained from (2) and (4) and plotted as a function of x in figures 1 and 2, respectively. It is noted that the values of coupling parameter (λ) remain almost constant throughout the range of composition (x) in $La_{2-x}(Ca,Na,K)_xCuO_4$. The values of $\lambda > 1{\cdot}0$ obtained by us are indicative of the fact that they have been obtained from the strong coupling mechanism. For $La_{2-x}Ca_xCuO_4$ superconductor, ω_c first increases up to $x = 0{\cdot}15$ and then decreases with increase of composition (x). In $La_{2-x}Na_xCuO_4$ the values of ω_c increase up to $x = 0{\cdot}50$. In contrast, its value in K-doped superconductors increases with increase of composition (x).

Using the values of the model parameters (λ, μ^* and ω_c) obtained for different compositions (x), we have computed T_c using (6) and plotted it as a function of x in figures 3 and 4. It is seen from these figures that our calculated values of T_c as a function of x are in reasonably good agreement with measured data on Ca (Bednorz *et al* 1987; Grover *et al* 1987; Moodenbaugh *et al* 1992), Na (Markert *et al* 1988; Subramaniam *et al* 1988) and K (Shibata *et al* 1990) dopings as they are indicated

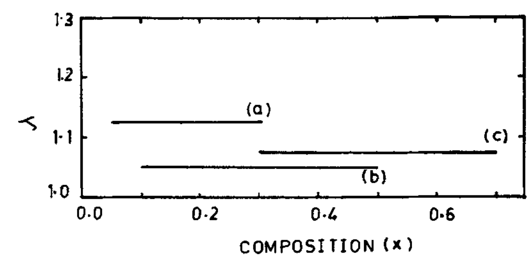

Figure 1. Variation of parameter λ with (a) Ca, (b) Na and (c) K composition (x).

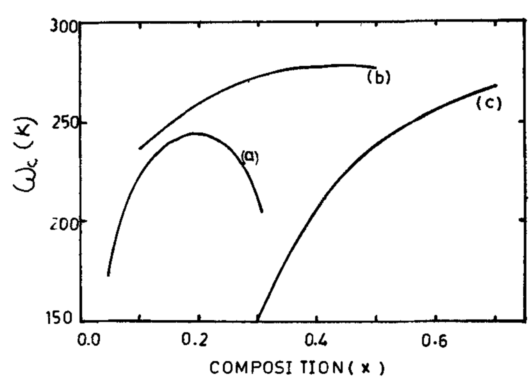

Figure 2. Variation of parameter ω_c with (a) Ca, (b) Na and (c) K composition (x).

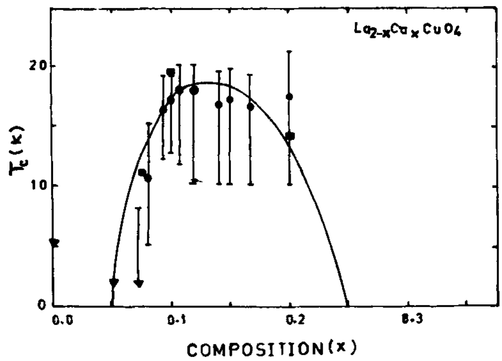

Figure 3. Variation of transition temperature (T_c) with composition (x) in $La_{2-x}Ca_xCuO_4$. The triangles (▼) and circles (●) are experimental data from Grover *et al* (1987) and Moodenbaugh *et al* (1992). The squares (■) are the experimental data taken from Bednorz *et al* (1987).

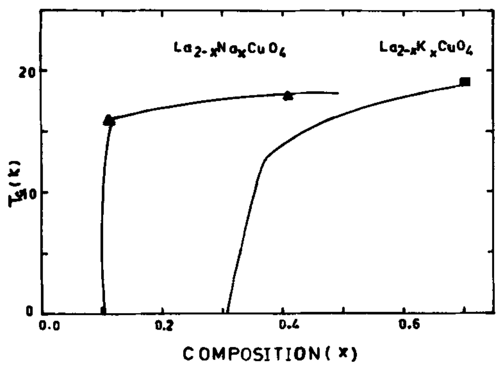

Figure 4. Variation of transition temperature (T_c) with composition (x) in $La_{2-x}Na_xCuO_4$ and $La_{2-x}K_xCuO_4$. The triangles (▲) are experimental data taken from Markert *et al* (1988) and the square (■) is experimental value from Shibata *et al* (1990).

in figures 3 and 4. Figure 3 shows that there is a maximum value of T_c (= 18 K) at $x = 0{\cdot}15$ in calcium doping and this agrees fairly well with the observed data (Bednorz *et al* 1987; Grover *et al* 1987; Moodenbaugh *et al* 1992). Besides this, T_c is zero for the compositions $x = 0{\cdot}05$ and 0·25. We find from figure 4 that T_c increases with Na composition and remains constant in the range $0{\cdot}10 \leqslant x \leqslant 0{\cdot}50$ with $T_c = 18$ K. These features are in keeping with those revealed from the experimental observation (Markert *et al* 1988) with $T_c = 16$ K (18 K) for $x = 0{\cdot}11$ (0·41). The appearance of superconductivity in the range $x \leqslant 0{\cdot}08$ obtained from our calculations of T_c is also consistent with the observations made by Markert *et al* (1988), Shibata *et al* (1990) and Subramaniam *et al* (1988) for composition range $x \leqslant 0{\cdot}08$. The $La_{2-x}K_xCuO_4$ system becomes superconducting for $x \geqslant 0{\cdot}03$ (see figure 4) and T_c increases with composition (x) with maximum value of $T_c = 19$ K at $x = 0{\cdot}7$. This feature agrees fairly well with the experimental observations (Shibata *et al* 1990).

Finally, it may be concluded that our FTEP, based on the pairing mechanism caused due to the charge carriers by the exchange of 2D acoustic plasmons, is capable of predicting the observed composition dependence of the transition temperature in

214 superconductors. These 2D acoustic plasmons are expected to play an important role also in describing the superconducting properties of 123 superconductors. Such investigations are in progress and the results will be reported subsequently.

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