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The variation of the transition temperature of high T_c superconductors by electric field effect

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High T_c superconductor is considered as an alternately stacked metal and insulating layers. The electric field effect in this layer superconductor is investigated by the Thomas-Fermi(TF) approximation for the screening of an applied electric field and in the frame of Ginzburg-Landau(GL) theory with the coupling between metallic layers for the transition temperature. The change of the transition temperature related to the coupling constant and applied voltage is derived for two and three CuO_2 layers. The transition temperature for more than three layers is also briefly discussed.

1. INTRODUCTION

Electric field induced charge effects to superconductors were studied back to 1960. The changes in conventional superconducting transition temperature T_c were extremely small due to the electric field penetration length of less than $1\AA$. The discovered high T_c oxide superconductors lightened a new wave to get large electric field effects due to the low carrier density and thus larger penetration length of around ten of $\AA$ and small coherence length. Therefore, the shift of the critical temperature of the high-temperature superconductors(HTSC) is easily observed.

Up to the present time,the mechanism causing the large electric field effects is most accepted to be the charge modulation model.[1] The usual approach is to use BCS weak coupling model, TF model and Poisson equation for a weaker anisotropic HTSC. Sakai[2]used TF model and regarded HTSC as consisting of alternately stacked N superconducting and N insulating layers(thickness d). The present short report uses TF model, g_3 interlayer coupling model[3] and plasmon BCS-like mechanism to simulate the field effect of the change of T_c in HTSC. Such an approach is an attempt to relate the electric field effect to the superconducting mechanism.

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Our approach is briefly described in Sec-II. The results and discussion is presented in Sec-III. Finally, a brief conclusion is made.

2. THEORY

Consider a system of a MIS like structure[2], there is a gate insulator with thickness L between the gate metal and HTSC. Assume, there is also an insulating layer $I_0$with thickness s between the gate insulator and the topmost CuO_2 layers. The CuO_2 superconducting layer is considered as a two dimensional.

By application of a gate voltage V, there is the charge density Q induced at the gate electrode is$Q = (v - \phi_1)\frac{\varepsilon_i \varepsilon_b}{\varepsilon_b L + \varepsilon_i s}$, where ϕ_1 is the potential of the topmost CuO_2 layer of HTSC, ε_i and ε_b are the dielectric constant of the gate insulator and the insulator layer I_o, respectively.

In the TF model, the induced charge density on the pth CuO_2 layer is $\delta n_p = e\phi_F \phi(r_{||}, z_p)$, where ϕ_F is density of states at the Fermi energy and $z_p = L + S + (p-1)d$. The origin of z axis is set at the gate metal and positive z axis is downward perpendicular to the surface of HTSC. The electrostatic potential $\phi(r_{||}, z)$ at the position z may be determined by the Poisson equation[4]

$$\frac{d^2\phi}{dz^2} = -\frac{Q}{\varepsilon_i}\delta(z) + \frac{\varepsilon_s Q - \varepsilon_b(Q - e^2\phi_F\phi(z))}{\varepsilon_b\varepsilon_s\delta(z - z_1)}$$

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$$+\frac{e^2\phi_F}{\varepsilon_s}\sum_{p=2}^{N}\phi(z)\delta(z-z_p)+\frac{\phi_N(z_N)}{d}\delta(z-z_{N+1})$$

where ε_s is the dielectric constant of the insulator inside HTSC. ϕ_N is the potential between Nth CuO_2 layer and $(N+1)$ th CuO_2 layer. While $z \neq 0$ and $z \neq z_p$, the Poisson equation becomes Laplace equation. The solution of this equation is $\phi_p(z) = A_p(z-z'_p)+B_p$, where z'_p is a reference coordinate and may be taken to be $z'_p = z_p + \frac{d}{2}$, By using Gauss's law, and the continuity of the potential

$$\phi_p(z_{p+1}) = \phi_{p+1}(z_{p+1}) = \phi(z_{p+1})$$

then we have the recurrence relation among A_p, B_p, A_1 and B_1. To understand the change of T_c of HTSC with the applied electric field, several situations will be discussed separately as following.

(i)only one CuO_2 layer

The Fermi energy will be modified in the TF approximation as $E_F = E_F^o + e\phi_1$, where E_F^o is the Fermi energy of HTSC without applied voltage. T_c of HTSC can be gotten by plasmon mechanism. $T_c = 1.134 E_F \exp(-1/\lambda)$, where λ is a coupling constatn depending on the Fermi energy. The essential change of T_c with applied electric field shows a linear behavior.

(ii)only two CuO_2 superconducting layers

In this situation, we use th GL theory approach to get T_c of HTSC. The free energy density f of HTSC according to the g_3 model[3] is

$$f = \alpha\sum_{i=1}^{2}(T-T_{ci})|\psi_i(z_i)|^2 - g_3[\psi_1^*(z_1)\psi_2(z_2) + c.c.]$$

where $T_{ci} = 1.134 E_{Fi}\exp(-1/\lambda_i)$,
$E_{Fi} = E_F^o + e\phi_i,\ i = 1, 2,;\ \psi_1(z_1)$ and $\psi_2(z_2)$ are order parameter on 1st and 2nd CuO_2 layer respectively. g_3 is interlayer coupling constant and assumed to be negligible for field effect. The T_c can be obtained by minimizing free energy with respect to $\psi_1^*(z_1)$ and $\psi_2^*(z_2)$. Then T_c is

$$T_c = \frac{1}{2}[(T_{c1}+T_{c2}) + \sqrt{(T_{c1}-T_{c2})^2 + 4(g_3/\alpha)^2}]$$

(iii)More than three CuO_2 layers

According to the result of Sakai[2], the electric field effect is limited within three superconducting CuO_2 layers. The free energy F of more than three CuO_2 layers may be easily expressed. Then minimizing F with respect to ψ_p^*, we may get the linear system equations and finally T_c can be gotten.

3. RESULTS and DISCUSSION

For one CuO_2 layer, T_c increases linearly as electric field E increases in plasmon mechanism. For two CuO_2 layers, the interlayer coupling strength g_3 affects T_c, but the sign of g_3 does not change T_c. The change of T_c deviates slightly from that in one CuO_2 layer. For more than three CuO_2 layers, the T_c value may be calculated by Ginzbung-Landau theory and taken into account the effect of Debye screening length. The expression of T_c is not shown here. But the qualitative behavior of the change of T_c due to the applied field is essentially limited to two or three CuO_2 layers. Because the Debye screening length is almost 5Å in most HTSC. Our present approach may be extended to the other mechanisms.

4. CONCLUSION

T_c of HTSC in an applied electric field is derived on the basis of plasmon mechanism in the framework of TF model and g_3 interlayer coupling model. The qualitative behavior of the change of T_c is shown linearly with the electric field E and independent of the sign of g_3 for one or two CuO_2 layers. The electric field effect on HTSC is essentially limited within the Debye screening length. Our approach may be easily extended to other mechanism.

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