Photoinduced superconductivity in copper oxides with two-component scenario

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Abstract. We investigated the photostimulated superconducting phase transition temperature ($T_c$) in copper oxides with the two-component scenario. In the two-component model, superconductivity is caused by the interband repulsive electron-lattice and Coulomb interaction. The photoexcitation produces a change of the hole doping ($p$) and as a result the shift $\Delta T_c$ of $T_c$ of copper oxides. The $T_c$ change is determined by the sign of $dp/dT_c$ and can be explained in terms of the phase diagram. The theory is compared with the available experimental data.

1. Introduction
Since the beginning of the 1960’s there has been an ongoing effort to use static transverse electric field to modulate the superconducting properties of films [1-7]. Considerable attention has been focused on the idea of modulating the carrier density and the superconducting properties of high-$T_c$ cuprates by electric field effects [1-7] or photoexcitation [8-16]. Many photoconductivity experiments have been carried out, for example, on insulating YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) single crystals [8-16] and La$_2$CuO$_4$ single crystals [13]. In YBa$_2$Cu$_3$O$_{6.1}$ single crystals irradiated by laser pulses, a photoinduced increase in conductivity of more than 10 orders of magnitude with the lifetime of 10-50 ns was observed [12]. A more striking phenomenon, persistent photoconductivity (PPC) in the semiconducting phase of YBCO thin films with $x=0.6$, was discovered by Kudinov et al. [8-10]. In the PPC state, the excess conductivity persists a long time after switching off the lights [8]. The photoinduced enhancement of superconductivity was confirmed in YBCO thin films with an initial $T_c$ of less than 25 K [13] and then in the films with a $T_c$ of as high as 82 K [13]. Two different time regimes have been explored experimentally. The first involves the photoexcitation of the sample with very short laser pulses (~0.6 ns) with the photon density $Q \approx 10^{13} - 10^{16}$ photons/cm$^2$ [12] in each pulse. In these experiments, the excess carriers are photogenerated during short periods of time, giving a rise to transient photoconductivity changes (~1 ns) insulating YBCO single crystals of more than 10 orders of magnitude [8-10]. Also a deep minimum in the temperature dependence of the photoinduced resistivity has been observed near 90 K, indicative of transient photoinduced superconductivity. In the second type of experiments, a continuous-wave laser is used to illuminate thin films during long periods of time (5-40 h) with total doses $Q \approx 10^{18} - 10^{23}$ photons/cm$^2$ [12]. In contrast to the pulse excitation experiments, the excess photoconductivity is persistent (PPC) in time at low temperatures and it saturates as a function of an increasing photon dose [12].
In this paper we consider the photoinduced phenomena as a result of photodoping [14,15] in terms of the phase diagram as in the case of the electrostatic field effects phenomena [7].

2. The Hamiltonian and doping dependence of $T_c$

The mechanism of high-$T_c$ superconductivity (HTSC) has been extensively studied but HTSC in cuprates is still to be being understood theoretically. One of the approaches for the high-$T_c$ superconductivity in cuprates, at present, is the two-component scenario [17-22]. Two different electronic subsystems have been found to be active. One of them corresponds to an itinerant type of carriers, the other is a narrow-flat [23] band of polaronic nature. There is an experimental evidence, indicative of a participation of several bands in the onset of superconductivity in cuprates: (i) the thermopower has a wide band and a narrow band contributions [23]; (ii) measurements of the microwave surface impedance in the superconducting state of Y-123 have revealed a two-gap superconductivity [24]; (iii) a femtosecond optical response contains two distinct components [25]. In [7,21,22] the s-wave pairing in the two-band model, which reproduces the nodes in the gap connected with the single-band d-wave pairing, has been considered. In accordance with [7,20,21], the superconductivity is induced by an interband repulsive electron-lattice and Coulomb interaction and a remarkable volume of the Brillouin zone contributes to the pairing.

We start with the Hamiltonian ($\sigma = 1, 2$)

$$H_0 = \sum_{\sigma, k, \lambda} \tilde{\varepsilon}_\sigma(\tilde{k}) a_{\sigma\lambda}^+ a_{\sigma\lambda} + 2W \sum_{\sigma, \sigma'} \sum_{k, k'} a_{\sigma\lambda}^+ a_{\sigma'\lambda'}^+ a_{\sigma'\lambda'} a_{\sigma\lambda},$$  \hspace{1cm} (1)

Here $\tilde{\varepsilon}_\sigma(\tilde{k}) = \varepsilon_\sigma(\tilde{k}) - \mu$, $\mu$ is the chemical potential, $s = \uparrow, \downarrow$ are the spin projections, $W$ is the effective pair-transfer electron-electron interaction constant describing the scattering of the pairs of electrons (holes) with the opposite spins ($s'$) and the wave vectors from $\sigma = 1$ band to $\sigma = 2$ band and vice versa. For the inclusion of the intraband interactions and for the account of the anisotropy see [20,26].

Using Eq.(1) we obtain the free energy [27]

$$F = \sum_{\sigma} \left\{ \sum_k \left[ \tilde{\varepsilon}_\sigma(\tilde{k}) - 2k_B T \ln(2 \cosh(E_\sigma(\tilde{k})/2k_B T)) \right] + \right.$$ \hspace{1cm} \left. + |\delta_\sigma|^2 \eta_\sigma(|\delta_\sigma|, T) \right\} - \frac{W}{2} \eta_1(|\delta_1|, T) \eta_2(|\delta_2|, T) \times \left[ \delta_1^* \delta_2 + \delta_1 \delta_2^* \right]$$  \hspace{1cm} (2)

where

$$E_\sigma(\tilde{k}) = \left[ \tilde{\varepsilon}_\sigma^2(\tilde{k}) + |\delta_\sigma|^2 \right]^{1/2},$$ \hspace{1cm} (3)

$$\eta_\sigma(|\delta_\sigma|, T) = \sum_k \frac{\tanh(E_\sigma(\tilde{k})/2k_B T)}{E_\sigma(\tilde{k})}$$ \hspace{1cm} (4)

The minimization of the free energy $F$ with respect to $\delta_\sigma$ gives the system of equations for gaps $\Delta_{1,2}$

$$\begin{align*}
\Delta_1 &= -W \Delta_2 \eta_2(|\Delta_2|, T) \\
\Delta_2 &= W \Delta_1 \eta_1(|\Delta_1|, T)
\end{align*}$$ \hspace{1cm} (5)
where $\Delta_{1,2}$ are the equilibrium superconducting gap order parameters.

The quantity $W(k', k)$ has been supposed to be operative and constant in the energy intervals $\{ -\Gamma_1, -\Gamma_2 \}$ for the higher band ($\sigma = 1$) and $\{ -\Gamma_3, -\Gamma_4 \}$ for the lower one ($\sigma = 2$) at which $0 \leq \Gamma_1 < \Gamma_3 < \Gamma_{2,4}$. The equation for $T_c$ ($\zeta = -\mu$; $\zeta$ is the chemical potential of holes [20]):

$$1 - W^2 \eta_1(0,T_c) \eta_2(0,T_c) = 0.$$  (6)

It follows for $\Gamma_1 < \zeta < \Gamma_3$ that

$$k_B T_c = 1.13(\zeta - \Gamma_1)^{1/2} (2 - \zeta)^{1/2} \exp \left[ - \frac{1}{2} \ln \left( \frac{\zeta - \Gamma_1}{(2 - \zeta)} \right)^{1/2} \right],$$  (7)

for $\Gamma_3 = \zeta$:

$$k_B T_c = 1.13(\Gamma_4 - \zeta)^{1/4} (\zeta - \Gamma_1)^{1/4} (2 - \zeta)^{1/4} \exp \left[ - \frac{1}{2} \ln \left( \frac{\zeta - \Gamma_1}{(2 - \zeta)} \right)^{1/2} \right],$$  (8)

and in the case of $\Gamma_{2,4} > \zeta > \Gamma_3$:

$$k_B T_c = 1.13(\zeta - \Gamma_3)^{1/4} (\zeta_3 - \zeta)^{1/4} (\zeta - \Gamma_1)^{1/4} (2 - \zeta)^{1/4} \exp \left[ - \frac{1}{2} \ln \left( \frac{\zeta - \Gamma_1}{(2 - \zeta)} \right)^{1/2} \right],$$  (9)

where

$$\kappa = \frac{1}{4} W^2 \rho_1 \rho_2.$$  (10)

and $\rho_1, \rho_2$ are the densities of states. Further, we suppose that in Eqs.(7)-(9) $\Gamma_1 = 0$, which corresponds to the top energy of the higher band ($\sigma = 1$) of the width $E_1$; $\Gamma_3 = E_0 - E_0$, is the top energy of the lower band ($\sigma = 2$) and $\Gamma_2 = \Gamma_4 = E_c, -E_c$ is the cut-off energy.

To proceed we need an expression connecting the concentration of the holes with the chemical potential $\zeta$. Supposing the holes to be highly degenerate, one obtains

$$\zeta = \frac{n_h}{\rho_1} + \frac{1}{2} E_1, \quad \text{if } \zeta \leq E_0,$$  (11)

$$\zeta = \frac{n_h + \rho_2 E_0 + \frac{1}{2} \rho_1 E_1}{\rho_1 + \rho_2}, \quad \text{if } \zeta > E_0.$$  (12)

For $\zeta = E_0$ the exact relation is

$$\zeta = \frac{n_h}{\rho_1} + \frac{1}{2} E_1 - \frac{\rho_2}{\rho_1} k_B T_c \ln 2.$$  (13)

Here $n_h$ must be treated as the number of holes in CuO$_2$ planes per cell added by doping, $E_1$ is the width of the band.

Further we consider the photoinduced effects in YBCO films introduced by the photodoping [15] for the case of PPC. The photodoping leads to the change of $n_h$ and as a result to a change of $T_c$. The
photoinduced shift of $T_c$ is treated in terms of the phase diagram as in the case of the electrostatic field effects [7]. Analogously in terms of the phase diagram the photoinduced shift of $T_c$ was considered in [28] for the proposed model with one wide band and two impurity bands depending specifically on $n_h$.

The shift $\Delta T_c^{PPC} = T_c^{PPC} - T_c$ is positive for $dT_c / dn_h > 0$ and negative for $dT_c / dn_h < 0$. The effect of white-light illumination on the transport properties of partially oxygen-depleted YBCO depends strongly on the temperature at which the photodoping experiment is performed. The photoassisted oxygen-ordering and charge transfer processes from CuO$_2$ planes to CuO chains are the main contributions to the PPC effect. It is also shown that the $T_c$ enhancement due to photodoping is a function of the carrier concentration rather than of the mobility. The experimental results are consistent with a photoassisted rearrangement of the oxygen ions in the chain planes being the mechanism responsible for the observed PPC [12,15].

The photodoped change of the carrier concentration

$$\Delta n_h^{PPC} = \frac{-\eta Q(t)}{1 + \gamma Q(t)},$$

where $\gamma$ and $\eta$ are coefficients.

The Whangbo and Torardi formula in [13] reported a quadratic relation $T_c = T_{c,\max} \left[1 - K(p - p_{opt})^2\right]$, between $T_c$ and $p$ estimated from the bond valence sum for several high-$T_c$ cuprates. In [29] it is given $\kappa = 82.6$, $p_{opt} = 0.16$.

We calculated the dependence of $\Delta T_c^{PPC}$ on the carrier concentration $p$ for YBCO, using the parameters $E_0 = 2.01$ eV, $E_1 = 2.23$ eV, $E_1 = 3.8$ eV, $\rho_1 = 0.75$ (eV)$^{-1}$, $\rho_2 = 2.2$ (eV)$^{-1}$, $W = 0.22$ eV. The results of the calculation are given in the figure 1.

![Figure 1](image.png)

Figure 1. The dependences of $\Delta T_c$ on $\Delta p$ for YBa$_2$Cu$_3$O$_x$ (our calculations, solid line), from $T_c(x)$ [12] (our calculations, dash line), from $T_c(\Delta p)$ [29] (our calculations, dash dot dot line) in comparison with the experimental data [12] (solid squares), [10] (solid triangles) and for GdBa$_2$Cu$_3$O$_x$ [30] (circles).

As we see, the theory describes the experiment satisfactorily.
Acknowledgments

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