# Electric field effects in high-$T_c$ cuprates

P. Konsin and B. Sorkin
*Institute of Physics, Riia 142, EE2400 Tartu, Estonia*
(Received 30 October 1997; revised manuscript received 6 April 1998)

Dependences of $T_c$ on hole concentration in $YBa_2Cu_3O_{7-y}$ (Y-123) and $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) cuprates have been calculated in the transverse electric field $\vec{E}$ in the framework of the two-band model. The phase space for the pair-transfer scattering between the overlapping bands is determined by the position of the chemical potential. The dependence of $T_c$ on the hole concentration $n_h$ has a maximum. The calculated $T_c(n_h)$ agree in $\vec{E}=0$ with the experiment in Bi-2212 and Y-123 cuprates. The electric-field effects in cuprates are considered with the use of $T_c(n_h)$. In metal-insulator-superconductor structures, the electric field induces changes in the carrier concentration and in the position of chemical potential. The field-induced shifts of $T_c$ depend on the strength and polarity of the electric field. For maximum field effect, the superconductor has to be away from optimal doping, i.e., maximum $T_c$, $dT_c/dn_h=0$, and has to be closer to the maximum of the slope $dT_c/dn_h$. The asymmetry $|\Delta T_c(\vec{E})|\neq|\Delta T_c(-\vec{E})|$ changes with $\vec{E}$. In agreement with experiment, the shifts $|\Delta T_c(\vec{E})|$ decrease when the film thickness increases. The field effects in both systems are similar, but in Bi-2212 they are stronger. The theory agrees qualitatively and, in some cases, quantitatively with experiment. The dependence of the ratio of surface and bulk conductivities on the film thickness ($d$) allows us to obtain quantitative agreement between the calculated $d$ dependence of $|\Delta T_c(\vec{E})|$ and the experimental data in Y-123 and Bi-2212. The influence of the photodoping on $T_c$ of cuprates and photoinduced superconductivity are discussed. [S0163-1829(98)01633-6]

## I. INTRODUCTION

Since the beginning of the 1960's there has been an ongoing effort to use transverse static electric fields to modulate the superconducting properties of films.[1–3] These activities were extended to the high-$T_c$ cuprates shortly after the discovery of these superconductors.[4–31] For example, the superconducting transition temperature $T_c$ of 5–10 nm-thick ($YBa_2Cu_3O_{7-y}$) (Y-123) and $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) films is shifted by several kelvin.[9,10,20,22,24] The effect is large (25–30 K) in a Y-123 film with weak links[16,18] for applied polarizations $P=\epsilon E\approx 2\times 10^8$ V/cm. Under these conditions the critical current density is changed by $\approx 30-50$ % at 4.2 K.[9,10,22,24] Here $\epsilon$ designates the dielectric constant of the gate insulator in the metal-insulator-superconductor structures. A notable increase of the superconducting transition temperature $T_c$ and the normal-state conductivity was observed in illumination experiments[32–38] on thin films of $YBa_2Cu_3O_{7-y}$. The illumination by a continuous-wave laser[33] gives $\Delta T_c\approx 8$ K. The mechanisms of these phenomena are expected to be similar.

Currently it is still being debated which mechanism induces these large electric and laser field effects. Two different mechanisms[13–15,23,26,30,31,39–41] have been proposed and it is not yet clear which one, or possibly the combination of the two, leads to the effects observed.

According to the first mechanism (see, e.g., Refs. 1, 15, 25, 40, and 41), the electric field interacts with the charge carriers via the Coulomb forces and directly influences their concentration $n_h$. The altered mobile carrier concentration in turn changes the superconducting transition temperature and order parameter(s) and thus leads to the observed field effects. Analogously, the photodoping induces the change of carrier concentration and leads to the change in superconducting properties.

The second mechanism[13,19] is based on an electric-field-induced oxygen rearrangement. Using a modification of the asymmetric next-nearest-neighbor Ising (ASYNNNI) model,[42] it was shown that considerable rearrangement of chain oxygen occurs upon the application of an external electric field, which causes a change in the doping of the $CuO_2$ planes in Y-123. As a result, the carrier concentration, which is related to the ordering of oxygen vacancies, is changed. A key point in this theory is the inclusion of an extra term in the Hamiltonian of ASYNNNI model to take into account the interaction between the electric field and the oxygen electric dipole moments. The existence of permanent dipole moments in Y-123 has been detected in several experiments[43–46] that indicated the existence of ferroelectricity, antiferroelectricity,[43,44,46,47] or relaxor ferroelectricity[45] in $YBa_2Cu_3O_{7-y}$. This is still a debated topic. As in any electronic device, the temporal response is determined by the $RC$ time constant, the product of the channel resistance and the gate capacitance. The model based on field-induced ordering of oxygen atoms predicts characteristic $RC$ times of the order of minutes. In Ref. 29 the measured value of the $RC$ time constant of the device on the base of Y-123 film equals 0.5 $\mu$s. This result is consistent with the interpretation of the field effects in the high-$T_c$ cuprates as a direct charge transfer by the electric field, but inconsistent with a model based on electric-field-induced rearrangement of oxygen atoms. One counterargument to a second mechanism contends that the oxygen binding energies are too high to be overcome by the suggested processes in this mechanism.

In Ref. 25 the electric-field effects in $Bi_2Sr_2CaCu_2O_{8+x}$ and $YBa_2Cu_3O_{7-y}$ films have been measured. It was shown

 

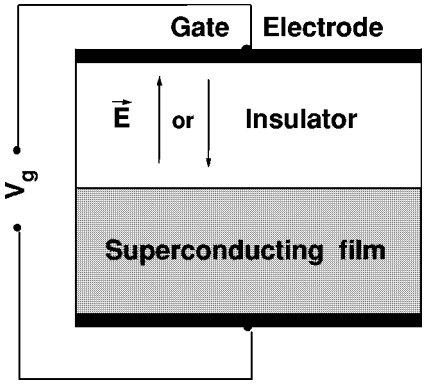


FIG. 1. The schematic cross section of the metal-insulator-superconductor field effect structure $V_g$ is applied perpendicular voltage.

that the field effects attained are rather similar. This provides direct evidence that in Y-123 and Bi-2212 superconductors the field effects are based on direct field-induced changes of carrier concentration $n_h$, which implies that the large electric-field effects are a generic property of the high-$T_c$ superconductors.

In this paper, we consider the electric-field effects in high-temperature superconducting films in metal-insulator-superconductor structures (see Fig. 1). We shall describe the situation microscopically in the framework of the two-band model. First we shall calculate the dependences of superconducting transition temperature in Bi-2212 and Y-123 on carrier concentration $n_h$ (Secs. II and III). Then we shall calculate electric-field-induced effects in superconducting films connected with the change of the chemical potential and, consequently, with the change of the carrier concentration in the electric field (Sec. IV). The electric-field effects in Bi-2212 and Y-123 are considered. The comparative analysis of field effects in these model superconductors Bi-2212 and Y-123 are made. The photoinduced superconductivity is discussed (Sec. V).

## II. MODEL

It is of fundamental importance to explain the doping dependence of the superconducting properties in cuprates. In this paper, the dependences of $T_c$ on the hole concentration $n_h$ in Bi-2212 and Y-123 systems have been calculated on the basis of the two-band model proposed for high-$T_c$ superconductivity in Refs. 48–50. The two-band model for high-$T_c$ superconductors has been known for a long time and for high-$T_c$ superconductors these ideas have been developed further (see, e.g., Refs. 48–53). In accord with Ref. 48, the superconductivity is induced by the interband coupling (in which the interband Coulomb contribution dominates) and a remarkable volume of the Brillouin zone contributes into pairing, in contrast to the BCS and the phonon interband attractive case. The free energy of this model in the mean-field approximation is written as[49]

$$F=\sum_{\sigma}\left(\sum_{\vec{k}}\left(\tilde{\epsilon}_{\sigma}(\vec{k})-2k_BT\,\ln\{2\cosh[E_{\sigma}(\vec{k})/2k_BT]\}\right)+|\delta_{\sigma}|^2\eta_{\sigma}(|\delta_{\sigma}|,T)\right)-\frac{W}{2}\eta_1(|\delta_1|,T)\,\eta_2(|\delta_2|,T)(\delta_1^*\delta_2+\delta_1\delta_2^*),\tag{1}$$

where

$$\eta_{\sigma}(|\delta_{\sigma}|,T)=\sum_{\vec{k}}\frac{\tanh[E_{\sigma}(\vec{k})/2k_BT]}{E_{\sigma}(\vec{k})},\tag{2}$$

$$E_{\sigma}(\vec{k})=[\tilde{\epsilon}_{\sigma}^2(\vec{k})+|\delta_{\sigma}|^2]^{1/2}.\tag{3}$$

The interband interaction constant $W$ is supposed to be independent of the wave vector $\vec{k}$. Here $\tilde{\epsilon}_{\sigma}(\vec{k})=\epsilon_{\sigma}(\vec{k})-\mu$; $\epsilon_{\sigma}(\vec{k})$ are the electron energies in the band $\sigma=1,2$; $\mu$ is the chemical potential. In Eqs. (1), (2), and (3), $\delta_{\sigma}$ are the non-equilibrium order parameters in which equilibrium values $\delta_{\sigma}=\Delta_{\sigma}$ are found from the minimization of the model free energy (1).

From the free energy (1), the equation determining $T_c$ follows ($\zeta=-\mu$ is the chemical potential of holes)

$$\kappa F(\Gamma_1-\zeta,\Gamma_2-\zeta)F(\Gamma_3-\zeta,\Gamma_4-\zeta)=1,\tag{4}$$

with

$$F(\Gamma_{\sigma}-\zeta,\Gamma_{\sigma'}-\zeta)=\int_{\Gamma_{\sigma}-\zeta}^{\Gamma_{\sigma'}-\zeta}\frac{dE}{E}\tanh\frac{E}{2k_BT_c},\tag{5}$$

$$\kappa=\tfrac{1}{4}W^2\rho_1\rho_2.\tag{6}$$

It is supposed that the limits of integration in Eq. (5) for the higher band ($\sigma=1$) are $\{-\Gamma_1,-\Gamma_2\}$ and for the lower one ($\sigma=2$), $\{-\Gamma_3,-\Gamma_4\}$. The densities of states $\rho_{\sigma}$ per spin are supposed to be constant.

We consider the case when $\Gamma_1=0$ fixes the top energy of the higher band of the width $E_1$, $\Gamma_3=E_0$, where $-E_0$ is the top energy of the lower band and the cutoff energy $-E_c$ determines $\Gamma_2=\Gamma_4=E_c$. As in Refs. 48–50, the superconducting transition temperature for the actual case $E_0<\zeta<E_c$ equals

$$k_BT_c=1.14[\zeta(\zeta-E_0)]^{1/4}(E_c-\zeta)^{1/2}\times\exp\left[-\frac{1}{2}\left(\frac{1}{4}\ln^2\frac{\zeta}{\zeta-E_0}+\kappa^{-1}\right)^{1/2}\right].\tag{7}$$

In Ref. 48 this expression and two equations for $E_0>\zeta$ and $E_0=\zeta$ have been used for the description of the $T_c(n_h)$ dependence in $La_{2-x}M_xCuO_4$ and $YBa_2Cu_3O_{7-y}$. Here we consider clean and impurity doped Bi-2212 and improved results for Y-123.

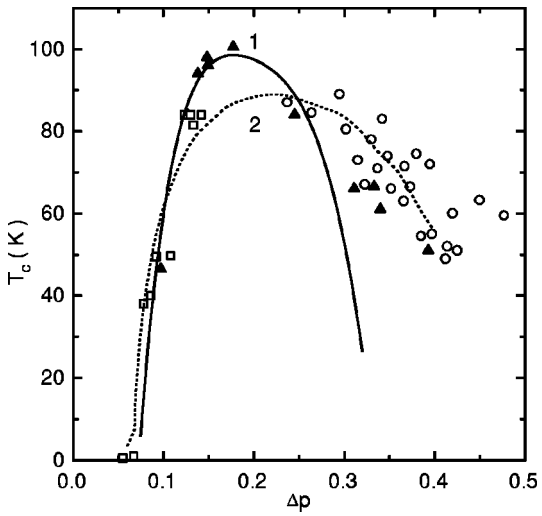


FIG. 2. The theoretical dependences of $T_c$ on the hole concentration $\Delta p$ for pure Bi-2212 (curve 1) and doped Bi-2212 (curve 2) in comparison with the experiment for pure Bi-2212 (triangles) (Ref. 55), Bi-2212-Y,Tm (squares) (Ref. 56), and Bi-2212-Na,K (circles) (Ref. 56).

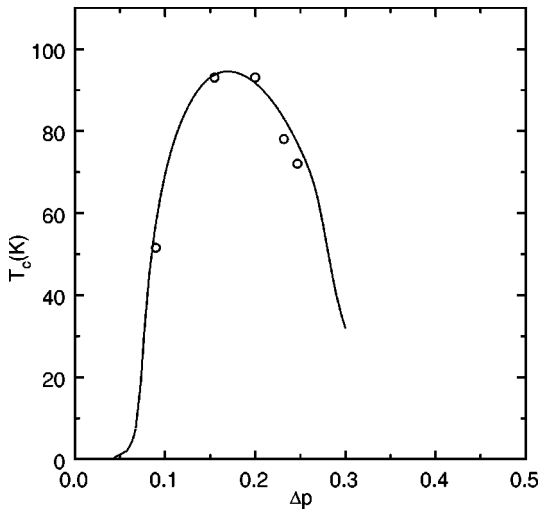


FIG. 3. The theoretical dependence of $T_c$ on the hole concentration $\Delta p$ for Y-123 (solid line) in comparison with the experiment (circles) (Ref. 56).

## III. DEPENDENCE OF $T_c$ ON CARRIER CONCENTRATION AT $\vec{E}=0$

The necessary relations between $\zeta$ and $n_h$ look like[48]

$$\zeta=\frac{n_h}{\rho_1}+\frac{1}{2}E_1, \quad \text{if } \zeta<E_0, \tag{8}$$

$$\zeta=(\rho_1+\rho_2)^{-1}(n_h+\rho_2E_0+\tfrac{1}{2}\rho_1E_1), \quad \text{if } \zeta>E_0, \tag{9}$$

$$\zeta=\left(\frac{n_h}{\rho_1}+\frac{1}{2}E_1-\frac{\rho_2}{\rho_1}k_BT\ln 2\right), \quad \text{if } \zeta=E_0. \tag{10}$$

Here $n_h$ is treated as the number of holes per cell, which are added by doping to $CuO_2$ planes in $YBa_2Cu_3O_{7-y}$ and $Bi_2Sr_2CaCu_2O_{8+x}$.

The assumption of the homogeneous distribution of the charge density across the samples is good approximation in high-$T_c$ superconductors with two $CuO_2$ layers ($m=2$) in the unit cell (Ref. 54). In analogy with graphite intercalation compounds, the charge distribution is strongly inhomogeneous for $m\geqslant 3$ ($Tl_2Ba_2Ca_{m-1}Cu_mO_{2m+4}$) with a depletion in the central layers (Ref. 54). In our model the effective (average) chemical potential appears, which corresponds to the average carrier concentration $n_h$. In experiments (Refs. 55 and 56), the dependence of $T_c$ on the average carrier concentration $n_h$ is determined (the homogeneous picture). Smooth variation of superconducting properties with doping (carrier concentration) and the absence of the phase separation from microscopic probes favor a uniform phase for doped cuprates (Ref. 57).

Using Eqs. (4) and (7), the dependences of $T_c(n_h)$ for pure Bi-2212 and impurity doped Bi-2212 are calculated (see Fig. 2, $\Delta p=n_h/2$). We use the following densities of states $\rho_1=1.0\ (\text{eV})^{-1}$, $\rho_2=2.2\ (\text{eV})^{-1}$, the width of the higher band $E_1=4$ eV, and fitting parameters $W=0.22$ eV, $E_c=2.33$ eV, $E_0=2.18$ eV for clean Bi-2212 and $\rho_1=1.0\ (\text{eV})^{-1}$, $\rho_2=2.2\ (\text{eV})^{-1}$, $W=0.19$ eV, $E_c=2.39$ eV, $E_1=4.0$ eV, $E_0=2.15$ eV for Bi-2212-Y,Tm and Bi-2212-Na,K. As follows from fitting for both cases, the lower band is narrow (cf. Ref. 58). As seen from Fig. 2, good fitting of the experimental data by the theoretical curves can be achieved in both cases. The difference between the two cases is mainly connected with the different values of $W$. Optimally doped clean Bi-2212 and Bi-2212-Y,Tm; Bi-2212-Na,K have $\Delta p=n_h/2=0.17$ and 0.22, respectively. As follows from Fig. 2, the dependence $T_c(n_h/2)$ for pure Bi-2212 and impurity doped Bi-2212 are not reduced exactly to the universal behavior $T_c(n_h/2)/T_{cmax}(n_h/2)$ proposed in Ref. 59. In the model of Ref. 48, the shift of the chemical potential with the carrier concentration changes the phase volume for pair-transfer scattering of electrons between the bands and leads to the observed dependence of the superconducting transition temperature $T_c$ on $n_h$. The maximum of $T_c(n_h)$ corresponds to $\zeta$ lying in the common region of both bands roughly in the middle between $E_0$ and $E_c$.

For the $YBa_2Cu_3O_{7-y}$ superconductor we use the parameter values $\rho_1=0.9\ (\text{eV})^{-1}$, $\rho_2=2.2\ (\text{eV})^{-1}$, $W=0.23$ eV, $E_c=2.33$ eV, $E_1=4.0$ eV, and $E_0=2.18$ eV. This set of parameters differs slightly from that used in Ref. 48. The calculated dependence of $T_c$ on $\Delta p$ for Y-123 in comparison with the experimental data is depicted in Fig. 3. The agreement is good. Using the relations between $n_h$ and the oxygen content $y$ given in Refs. 48 and 59, the dependence $T_c(y)$ can also be reproduced in agreement with the experiment.

## IV. INFLUENCE OF THE ELECTRIC FIELD ON $T_c$

Electrostatic screening, as described in the Thomas-Fermi model, counteracts the penetration of the electric field into a superconducting film and thus reduces the field effects. The Thomas-Fermi charge screening length equals

$$l_{TF}=\left(\frac{\hbar^2\pi\epsilon_s}{4m_ek_Fe^2}\right)^{1/2}=\left(\frac{\epsilon_sE_{F0}}{4\pi^2e^2n_0}\right)^{1/2}, \tag{11}$$

where $\epsilon_s$ is the dielectric constant of superconductor; $E_{F0}$ and $n_0$ are the Fermi energy and the carrier concentration in

the sample in the absence of the external electric field ($\vec{E}=0$), respectively, and $e$ is the electron charge. In some papers,[14,15,23,30] $l_{TF}$ is called the Debye penetration length $l_d$, but actually $l_d=(\epsilon_s k_B T/4\pi e^2 n_0)^{1/2}$ and $l_{TF}$ for metals and degenerate semiconductors has to be used. For Y-123, the carrier concentration $n_0 \sim 5\times 10^{21}$ cm$^{-3}$, $\epsilon_s=26$, and thus $l_{TF}=5$ Å (Ref. 11). In Ref. 24 estimates of $l_{TF}=5-10$ Å have been obtained. In superconducting films of conventional metals, $l_{TF}<1$ Å, which leads to relatively small $\Delta T_c(\vec{E})$ in these metals. In Ref. 17 the penetration of the electric field into a $YBa_2Cu_3O_{7-y}$ electrode was shown to vary by as much as 100 Å in the temperature range 60 K $<T<$ 110 K (the authors of Ref. 17 were unable to specify a quantitative mechanism for this electric-field penetration effect). In high-$T_c$ superconductors the low density of charge carriers is advantageous, leading to relatively large screening lengths. Furthermore, the small coherence lengths of high-$T_c$ superconductors allow the fabrication of ultrathin films in which the total carrier density can be changed to a substantial extent. Correspondingly, the superconducting order parameter(s) can rapidly change (due to the small correlation length) to probe the field-penetrated area. An additional reduction in screening, attained, e.g., by using samples in which weak links[16,18] have been incorporated, can allow one to achieve even larger field effects. If a transverse electric field penetrates into a superconductor, its response to the field will depend sensitively on the value of the parameter $\tau=l_{TF}/\xi_z$, where $\xi_z$ is the coherence length in the field direction. In our model, the electric-field-induced effects are connected with the changes of the carrier concentration in the electric field and as a consequence with the change of the chemical potential $\zeta(\vec{E})$.

In the framework of the Thomas-Fermi approximation, it was obtained in Refs. 15, 23, and 30 for the carrier concentration of superconductor $n_s(z)$ in the field $E$ (the coordinate $\vec{z}\|\vec{E}$),

$$n_s(z)=n_0\frac{E}{E^*}\exp(-z/l_{TF}), \tag{12}$$

where $E^*=el_{TF}n_0/\epsilon\epsilon_0$, $\epsilon$ is the dielectric constant of the gate insulator, $e<0$, $E=V_g/l$, $V_g$ is the applied voltage, and $l$ is the thickness of the gate insulator.

Further, we suppose that the total charge induced by the electric field participates in conductivity and the surface and bulk mobilities of carriers are equal. This assumption is more justified in the case $\tau=l_{TF}/\xi_z \geqslant 1$. Then, using Eq. (12), the field-induced changes of the carrier concentration $\Delta n$ averaged over the thickness $d$ of a superconducting film is given by the expression

$$\Delta n=\frac{1}{d}\int_0^d n_s(z)dz=\frac{\epsilon\epsilon_0 E}{ed}(1-e^{-d/l_{TF}}). \tag{13}$$

It is clear that for $d \gg l_{TF}$ $\Delta n=\Delta Q/d$ (see also Refs. 24, 40, and 41), where $\Delta Q=e^{-1}\epsilon_0\epsilon E$ is the field-induced surface carrier density (for the surface layer).

The expression for the chemical potential $\zeta(\vec{E})$ follows from Eqs. (8)–(10) for $\zeta$ by replacing $n_h \to n_h+n_{\vec{E}}$ with $n_{\vec{E}}=v\,\Delta n$ equal to the number of holes (electrons) per cell of the volume $v$, i.e., the electric field changes the average carrier concentration $n_h$ in $CuO_2$ planes (electric-field doping). The thickness of superconducting films influences essentially $n_{\vec{E}}$ and the magnitude of the field-induced effects.

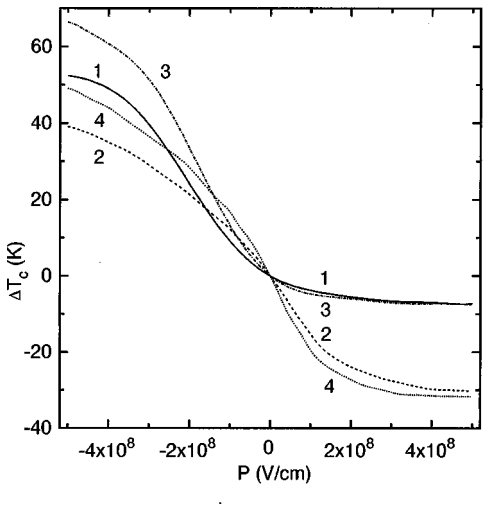


FIG. 4. The theoretical dependences of $\Delta T_c$ on polarization $P$ for Y-123 [$d=10$ nm, $T_c(0)=8$ K (curve 1); 31 K (2)] and for pure Bi-2212 [$d=18$ nm, $T_c(0)=8$ K (3); 32 K (4)].

Using Eq. (4), we obtain the equation for the superconducting temperature in the electric field by replacing $\zeta=\zeta(0)$ by $\zeta(\vec{E})$:

$$\kappa F[-\zeta(\vec{E}),E_c-\zeta(\vec{E})]F[E_0-\zeta(\vec{E}),E_c-\zeta(\vec{E})]=1. \tag{14}$$

The shift of the superconducting transition temperature of films in an electric field is defined as $\Delta T_c(\vec{E})=T_c(\vec{E})-T_c(0)$. In the positive electric field $E$, the carrier concentration $n_{\vec{E}}<0$ and, if $(dT_c/dn_h)>0$ (see Sec. III), it can be shown that $\Delta T_c(\vec{E})<0$. For the negative voltage $V_g$ $n_{\vec{E}}>0$ and $\Delta T_c(-\vec{E})>0$. In the case $(dT_c/dn_h)<0$, the shifts mentioned are opposite. This behavior correlates with experiment (Refs. 4, 8–11, 16, 18, 20, 24, 25, 27, and 29), which shows that the electric-field effects are indeed the bulk effects.

## V. CALCULATIONS FOR $Bi_2Sr_2CaCu_2O_{8+x}$ AND $YBa_2Cu_3O_{7-y}$

Next, on the base of Eqs. (13), (14), and the expression for $n_{\vec{E}}$, we calculate the dependences of the shifts $\Delta T_c(\vec{E})$ in $Bi_2Sr_2CaCu_2O_{8+x}$ and $YBa_2Cu_3O_{7-y}$ on the applied polarizations $P=\epsilon E$. Figure 4 shows that $\Delta T_c(\vec{E})$ strongly depends on $P$. At the positive electric field $\vec{E}$ and $(dT_c/dn_h)>0$, $\Delta T_c(\vec{E})<0$ in agreement with the experimental results (Refs. 8–11, 16, 18, 20, 25, and 27). For the negative voltages $-\vec{E}$, the shifts $\Delta T_c(-\vec{E})>0$ are also in agreement with the experiment (Refs. 9, 10, and 27). The asymmetry $|\Delta T_c(\vec{E})|\neq|\Delta T_c(-\vec{E})|$ takes place, which also agrees with experiment (Refs. 9, 18, and 27). For maximum electric-field effect, the carrier concentration in the superconducting film has to be away from optimal doping (see Figs. 2 and 3) and closer to the maximum of the slope $dT_c/dn_h$. At $P=2$

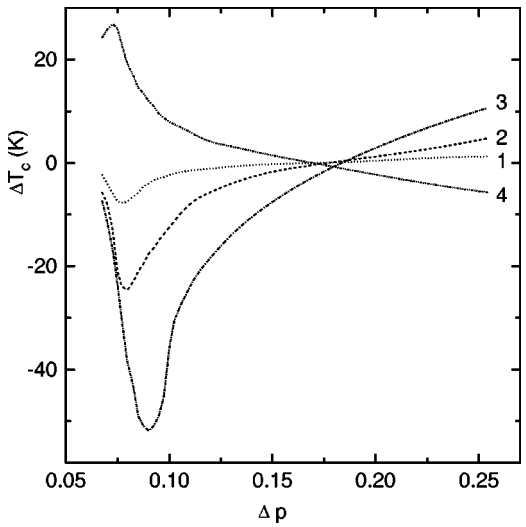


FIG. 5. The theoretical dependences of $\Delta T_c(\pm\vec{E})$ on $\Delta p$ for Y-123 at $d=10$ nm; $P=+5\times10^7$ V/cm (curve 1), $+2\times10^8$ V/cm (2), $+5\times10^8$ V/cm (3), and $-2\times10^8$ V/cm (4).

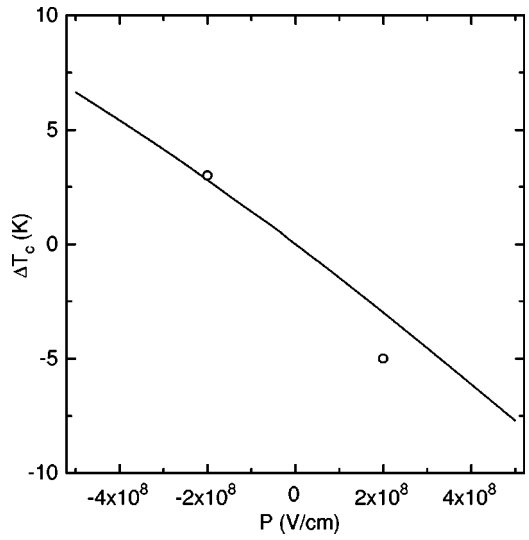


FIG. 6. The theoretical dependence of $\Delta T_c$ on $P$ for Y-123 at $d=100$ nm, $T_c(0)=31$ K (solid line) in comparison with the experiment (circles) (Ref. 27).

$\times10^8$ V/cm (such value of applied polarization $P$ is usually achieved in experiment) the saturation in the nonlinear dependence of $|\Delta T_c(\vec{E})|$ occurs at low $T_c(0)$, as observed in Ref. 25. More promising electric-field saturation in $|\Delta T_c(\vec{E})|$ is expected to occur at $|P|\geqslant5\times10^8$ V/cm. The saturation effect for the positive electric field (usually used in metal-dielectric-superconducting film structures) is connected with the existence of a tail of $T_c(n_h)$ (see Figs. 2 and 3) in the underdoped region. In this region the slope $dT_c/dn_h$ is small $[\zeta(\vec{E})<E_0]$ and the field-induced changes of carrier concentration $n_{\vec{E}}$ lead to small variations of $\Delta T_c(\vec{E})$. The saturation effects for negative polarizations are connected with the presence of the maxima $T_c(n_h)$ (see Figs. 2 and 3). In the region of $T_{max}(n_h)[\zeta(\vec{E})>E_0]$, the slope $dT_c/dn_h$ is small. Correspondingly, at these concentrations $n_h$ the superconducting transition temperature changes weakly with $n_h$. The shifts of the superconducting transition temperature in the electric field in Bi-2212 for a given $d$ are similar.

Figure 5 shows the field-induced shifts $\Delta T_c(\pm\vec{E})$ on the carrier concentration $\Delta p$ for Y-123. The occurrence of the minima [for $\Delta T_c(\vec{E})<0$] and of the maximum [for $\Delta T_c(\vec{E})>0$] is connected with the changes of slope $dT_c/dn_h$ with $\Delta p$ (see Figs. 2 and 3). The minima in $\Delta T_c(\vec{E})$ as a function of $\Delta p$ are caused by growing $|\Delta T_c(\vec{E})|$ with the carrier concentration $n_h$, which is maximal for the largest slope $dT_c/dn_h$, and with decreasing $|\Delta T_c(\vec{E})|$ in the underdoped region [the tail in the dependence of $T_c(n_h)$]. The small slope $dT_c/dn_h$ in the region of maxima $T_c(n_h)$ (see Fig. 3) is responsible for the maxima of $\Delta T_c(-\vec{E})$. Naturally, the magnitudes of $|\Delta T_c(\pm\vec{E})|$ in the extremal points ($\Delta p=0.08$ in Y-123 and $\Delta p=0.09$ in Bi-2212 for $P=2\times10^8$ V/cm) increase with the strength of the electric field. The minima of $\Delta T_c(+\vec{E})$ shift with the decrease of the electric field towards the underdoped region and this is a manifestation of the saturation effect. For the maxima of $\Delta T_c(-\vec{E})$ the effect is opposite.

Figure 6 shows the dependence of $\Delta T_c(\vec{E})$ on the applied polarization $P$ for a relatively thick $YBa_2Cu_3O_{7-y}$ film ($d=100$ nm). As seen from Fig. 6, the calculated $\Delta T_c(\vec{E})$ in Y-123 agree satisfactorily (practically without fitting parameters) with the experimental results[27] and reveal rather small asymmetry in comparison with the strong asymmetry of the experimental points (at $\pm E$ only two experimental points are available). Notice that $T_c(0)=31$ K corresponds to the experimental value.[27]

Figure 7 shows the dependence $\Delta T_c(\vec{E})$ in Y-123 with the carrier concentration $n_h=0.135$ and $T_c(0)=8$ K on the film thickness $d$ for the positive and negative voltages. The shifts $\Delta T_c(\vec{E})$ depend strongly on thickness $d$ because the field-induced carrier concentration [Eq. (13)] decreases with $d$.

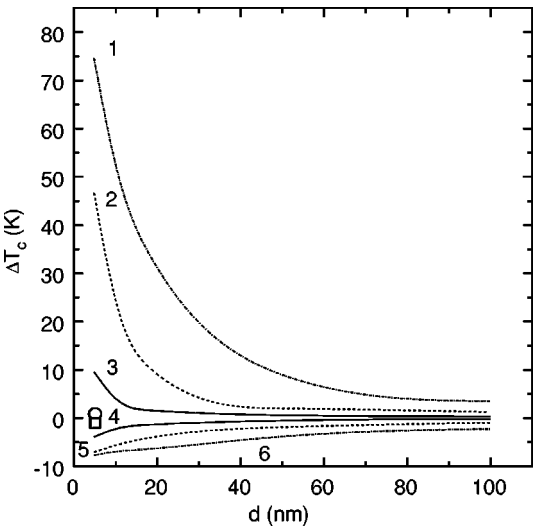


FIG. 7. The theoretical dependences of $\Delta T_c$ on thickness $d$ for Y-123 at $T_c(0)=8$ K; $P=-5\times10^8$ V/cm (curve 1), $-2\times10^8$ V/cm (2), $-5\times10^7$ V/cm (3), $+5\times10^7$ V/cm (4), $+2\times10^8$ V/cm (5), and $+5\times10^8$ V/cm (6) in comparison with the experimental data (circle for $P=-2\times10^7$ V/cm and square for $P=+2\times10^8$ V/cm) (Ref. 9).

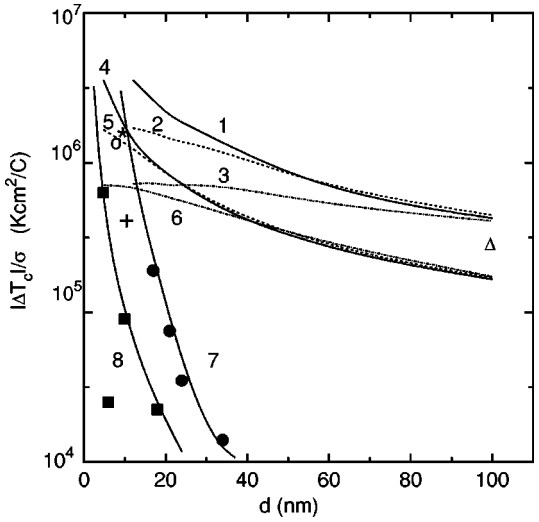


FIG. 8. The theoretical dependences of $|\Delta T_c|/\sigma$ on thickness $d$ for pure Bi-2212 at $T_c(0)=32$ K, $\sigma_s=\sigma_b$ [$P=+5\times10^7$ V/cm (curve 1), $+2\times10^8$ V/cm (2) and $+5\times10^8$ V/cm (3)]; for Y-123 at $T_c(0)=31$ K, $\sigma_s=\sigma_b$ [$P=+5\times10^7$ V/cm (4), $+2\times10^8$ V/cm (5), and $+5\times10^8$ V/cm (6)]; for pure Bi-2212, $\sigma_s\neq\sigma_b$ [$P=+2\times10^8$ V/cm (7)] and for Y-123, $\sigma_s\neq\sigma_b$ [$P=+2\times10^8$ V/cm (8)] in comparison with the experimental data for pure Bi-2212 (solid circles) (Ref. 25) and Y-123 (solid squares) (Ref. 25), star, open circle, cross (Refs. 9 and 18) and open triangle (Ref. 27).

We suppose that $T_c(0)$ does not depend on the film thickness $d$, i.e., $d\geqslant5$ nm (Ref. 60). As follows from our theory, the calculated dependences $\Delta T_c(\vec{E})$ on the thickness $d$ show similar tendencies, as in the experiment.[9]

We present the electric-field effects not only for Y-123 (Figs. 4–8) but also for Bi-2212 (Figs. 4 and 8). As follows from our calculations, the electric-field effects are similar in both compounds, supporting the conclusions of Frey *et al.*[25] We have also calculated the dependences of $\Delta T_c(\pm\vec{E})$ on the carrier concentration $\Delta p$ and $\Delta T_c$ on the film thickness $d$ for Bi-2212. The main difference between the electric-field effects in these materials is in the larger values of $|\Delta T_c(\pm\vec{E})|$ and $\Delta T_c(d)$ for Bi-2212 than for Y-123.

Figure 8 shows for the positive voltages the dependences of field-induced shifts $|\Delta T_c(\vec{E})|$ normalized to charge density $\sigma=\epsilon_0\epsilon E$ (added to gate electrode), i.e., $|\Delta T_c(\vec{E})|/\sigma$, on the film thickness $d$ for Y-123 and Bi-2212 cuprates. The agreement with the experimental data on ultrathin films by Mannhart *et al.*[8,10,16,18,25] and by Xi *et al.*[9,11,12] and for a thick film[27] is good. The agreement with the experiment is good, especially for an ultrathin film with weak links[16,18] (the larger electric-field penetration lengths). The normalized quantities $|\Delta T_c(\vec{E})|/\sigma$ in films with intermediate thickness $d$ is in satisfactory agreement with the experiment.

A good qualitative agreement with the experiment can be achieved introducing the surface and bulk conductivities (see below).

From our calculations it follows that the thickness $d$ of the superconducting films of Y-123 cuprates has to be by 1.5–2 times smaller than in the Bi-2212 cuprates in order to achieve the same effects, in agreement with the experiment with thin films.[25] Stronger electric-field effects in Bi-2212, in comparison with Y-123, are connected with the fact that the $n_{\vec{E}}$ is proportional to the unit-cell volume $v$, which is, in Bi-2212, 2.6 times larger than in Y-123. When $T_c(0)$ is lower (this case is not given in Fig. 8), the agreement with the experiment is better.

In Bi-2212-Y,Tm and Bi-2212-Na,K the electric-field effects are smaller than in pure Bi-2212. This is connected with the fact that the averaged $|dT_c/dn_h|$ (see Fig. 2) decreases with impurity doping. The quantities $|\Delta T_c(\vec{E})|/\sigma$ calculated for positive and negative voltages show asymmetry $|\Delta T_c(\vec{E})|\neq|\Delta T_c(-\vec{E})|$, which changes with the thickness $d$ and $\vec{E}$.

The less satisfactory agreement with the experiment for intermediate thickness $d$ can be explained by the following circumstance. The field-induced carrier concentration can be expressed as $n_{\vec{E}}\simeq v\Delta n(\sigma_s/\sigma_b)$ (cf. also Ref. 28), where the $\sigma_s$ and $\sigma_b$ are the surface (in the surface layer) and bulk conductivities, correspondingly. Above, we supposed that $\sigma_s=\sigma_b$ and, consequently, $n_{\vec{E}}=v\Delta n$, where $\Delta n$ is determined by Eq. (13). The case $\sigma_s\simeq\sigma_b$ has assumed high quality interfaces, absence of interface traps, defects, and ionic conduction. These are characteristics that can be achieved after considerable effort, as has been proven in semiconductor field-effect transistors. In the ultrathin films the larger $l_{TF}/d$ supports $\sigma_s\approx\sigma_b$, and in the thick films[27] the high quality of surfaces favors $\sigma_s\approx\sigma_b$.

We use the formula $\sigma_s/\sigma_b=B(d)=A/d^n$ where $B(d)<1$ (cf., e.g., Ref. 28). The defects and the inhomogeneities of the film surfaces lead to the decrease of $\sigma_s$ and a more rapid change of $T_c(\vec{E})$ on thickness $d$. The dependence of the ratio of surface and bulk conductivities on the film thickness allows us to obtain quantitative agreement between the calculated $d$ dependence of $|\Delta T_c(\vec{E})|/\sigma$ and the experimental data in Y-123 and Bi-2212 (see Fig. 8). We use the following fitting parameters in $\sigma_s/\sigma_b$: $A=8.5$ (nm)$^2$ and $n=2$ for Y-123 in field $E=2\times10^8$ V/cm and $A=6.5\times10^2$ (nm)$^3$, $n=3$ for Bi-2212, $E=2\times10^8$ V/cm. For the high quality surface $\sigma_s\simeq\sigma_b$ and $A=1$, $n=0$. As follows from our analysis, in experiments[25] Y-123 films were of higher quality than the Bi-2212 ones. The level of the film surface and the sample quality introduces some uncertainty in the experimental results and their reproducibility. However, the experimental data of Refs. 4, 8–11, 16, 18, 20, 24, 25, 27, and 29 are in qualitative agreement.

The calculated $|\Delta T_c(\pm\vec{E})|$ for the case $\sigma_s\neq\sigma_b$ are smaller [at $A=8.5$ (nm)$^2$ and $n=2$ for Y-123 by order of magnitude] than the electric-field shifts of $T_c$ presented in Figs. 4, 5, and 7 (the case $\sigma_s=\sigma_b$) but the shapes of the curves are retained.

The illumination causes photodoping[61] and leads to similar effects on $T_c$. Additional charge carrier (hole) concentration $2.5\times10^{19}$ cm$^{-3}$ can be photoexcited[62] inducing for $T_c(0)=19$ K in Y-123 the shift $\Delta T_c=7$ K calculated on the base of Eq. (14) (see also Ref. 39), i.e., $T_c$ increases in the laser field (in general the photoinduced Cooper pair breaking has to be taken into account). The photoexcited charge carrier concentration at a given time does not depend only on the number of photons in a laser pulse but also on the charge carrier lifetime and the pulse length. The short pulses,

$\sim 1$ ps, should be used.[62] A detailed consideration of the illumination effects will be done in a forthcoming work.

## VI. SUMMARY

In this paper the electric-field effects in cuprates are investigated. The dependences of the superconducting transition temperature on the carrier concentration $n_h$ at $\vec{E}=0$ are calculated for cuprates in the two-band model. The use of fitting parameters allows us to achieve good agreement of the dependence $T_c(n_h)$ with the experiment in $Bi_2Sr_2CaCu_2O_{8+x}$ and $YBa_2Cu_2O_{7-y}$ for $\vec{E}=0$. The electric-field effects themselves are calculated practically without any fitting parameters if $\sigma_s=\sigma_b$. As follows from our analysis, the number of fitting parameters of the theory in which the different surface and bulk conductivities are introduced is equal to 2 ($A$ and $n$). The other fitting parameters are used to fit the carrier concentration dependence of $T_c$ in Y-123 and Bi-2212 at $\vec{E}=0$. In our opinion, the number of fitting parameters used for the calculation of electric-field effects themselves does not exceed the ''critical'' value. The agreement of theoretical results with experiment is good and in some cases satisfactory. Some electric-field effects are predicted: $\Delta T_c(\vec{E})$ dependence on carrier concentration, the saturation effect, etc. The theory strongly supports the mechanism of the influence of the electric field on the superconducting temperature via inducing the change in the carrier concentration directly by Coulomb forces. In nonequilibrium conditions, the contribution from the field-induced rearrangement of oxygen in Y-123 into $\Delta T_c(\vec{E})$ is not excluded.

## ACKNOWLEDGMENTS

We thank N. Kristoffel, A. Sherman, P. Rubin, and M. Ausloos for discussions. This work was partially supported by the Estonian Science Foundation Grant No. 1929.

[1] R. E. Glover and M. D. Sherrill, Phys. Rev. Lett. **5**, 248 (1960).
[2] H. L. Stadler, Phys. Rev. Lett. **14**, 979 (1965).
[3] A. T. Fiory and A. F. Hebard, Phys. Rev. Lett. **52**, 2057 (1984).
[4] A. T. Fiory, A. F. Hebard, R. H. Eick, P. M. Mankiewich, R. E. Howard, and M. L. O'Malley, Phys. Rev. Lett. **65**, 3441 (1990).
[5] U. Kabasawa, K. Asano, and T. Kobayashi, J. Phys. Soc. Jpn. **29**, L86 (1990).
[6] A. Levy, J. P. Flack, M. A. Kastner, W. J. Galagher, A. Gupta, and A. W. Kleinsasser, J. Appl. Phys. **69**, 4439 (1991).
[7] Y. Tarutani, S. Saitoh, T. Fukuzawa, and U. Kawabe, J. Appl. Phys. **69**, 1778 (1991).
[8] J. Mannhart, J. G. Bednorz, K. A. Müller, and D. G. Schlom, Z. Phys. B **83**, 307 (1991).
[9] X. X. Xi, Q. Li, C. Doughty, C. Kwon, S. Bhattacharya, A. T. Findikoglu, and T. Venkatesan, Appl. Phys. Lett. **59**, 3470 (1991).
[10] J. Mannhart, D. G. Schlom, J. G. Bednorz, and K. A. Müller, Phys. Rev. Lett. **67**, 2099 (1991).
[11] X. X. Xi, C. Doughty, A. Walkenhorst, C. Kwon, Q. Li, and T. Venkatesan, Phys. Rev. Lett. **68**, 1240 (1992).
[12] A. Walkenhorst, C. Doughty, X. X. Xi, Q. Li, C. J. Lobb, S. N. Mao, and T. Venkatesan, Phys. Rev. Lett. **69**, 2709 (1992).
[13] N. Chandrasekhar, Oriol T. Valls, and A. M. Goldman, Phys. Rev. Lett. **71**, 1079 (1993); Phys. Rev. B **49**, 6220 (1994).
[14] B. Ya. Shapiro and I. B. Khalfin, Physica C **209**, 99 (1993).
[15] L. Burlachkov, I. B. Khalfin, and B. Ya. Shapiro, Phys. Rev. B **48**, 1156 (1993).
[16] J. Mannhart, J. Ströbel, J. G. Bednorz, and Ch. Gerber, Appl. Phys. Lett. **62**, 630 (1993).
[17] W. G. Jenks and L. R. Testardi, Phys. Rev. B **48**, 12 993 (1993).
[18] J. Mannhart, J. G. Bednorz, K. A. Müller, D. G. Schlom, and J. Ströbel, J. Alloys Compd. **195**, 519 (1993).
[19] A. Walkenhorst, M. Schmitt, H. Adrian, and K. Petersen, Appl. Phys. Lett. **64**, 1871 (1994).
[20] V. C. Matijasevic, S. Bogers, N. Y. Chen, H. M. Appelboom, P. Hadley, and J. E. Mooij, Physica C **235-240**, 2097 (1994).
[21] K. Joosse, Yu. M. Boguslavskij, G. J. Gerritsma, and H. Rogalla, Physica B **194-196**, 83 (1994).
[22] W. Kula and R. Sobolewski, Phys. Rev. B **49**, 6428 (1994).
[23] B. Ya. Shapiro, J. B. Khalfin, and L. Burlachkov, Physica B **194-196**, 1893 (1994).
[24] V. V. Lemanov and A. L. Kholkin, Fiz. Tverd. Tela (Leningrad) **36**, 1537 (1994).
[25] T. Frey, J. Mannhart, J. G. Bednorz, and E. J. Williams, Phys. Rev. B **51**, 3257 (1995).
[26] M. Ghinovker, V. B. Sandomirsky, and B. Ya. Shapiro, Phys. Rev. B **51**, 8404 (1995).
[27] E. H. Taheri, J. W. Cochrane, and G. J. Russel, J. Appl. Phys. **77**, 761 (1995).
[28] N. A. Tulina, G. A. Emelchenko, and A. B. Kulakov, Phys. Lett. A **204**, 74 (1995).
[29] R. Schneider and R. Auer, Appl. Phys. Lett. **67**, 2075 (1995).
[30] A. L. Rakhmanov and A. V. Rozhkov, Physica C **267**, 233 (1996).
[31] W. D. Lee, J. L. Chen, T. J. Yang, and Bi-Shion Chiou, Physica C **261**, 167 (1996).
[32] V. I. Kudinov, I. L. Chaplygin, A. I. Kirilyuk, N. M. Kreines, R. Laiho, E. Lähderanta, and C. Ayache, Phys. Rev. B **47**, 9017 (1993).
[33] E. Osquiguil, M. Macnhoudt, B. Wuyts, Y. Bruynseraede, D. Lederman, and I. K. Schuller, Phys. Rev. B **49**, 3675 (1994).
[34] J. Hasen, D. Lederman, I. K. Schuller, V. Kudinov, M. Macnhoudt, and Y. Bruynseraede, Phys. Rev. B **51**, 1342 (1995).
[35] K. Tanabe, S. Karimoto, S. Kubo, K. Tsuru, and M. Suzuki, Phys. Rev. B **52**, R13 152 (1995).
[36] J. F. Federici, D. Chew, B. Welker, W. Savin, J. Gutierrez-Solana, and T. Fink, Phys. Rev. B **52**, 15 592 (1995).
[37] W. Göb, W. Lang, W. Markowitsch, V. Schlosser, W. Kula, and K. Sobolewski, Solid State Commun. **96**, 431 (1995).
[38] R. Adam, W. Kula, R. Sobolewski, J. M. Murduck, and C. Pettiette-Hall, Appl. Phys. Lett. **67**, 3801 (1995).
[39] G. Grigelionis, E. E. Tornau, and A. Rosengren, Phys. Rev. B **53**, 425 (1996).
[40] P. Konsin, Physica C **235-240**, 1437 (1994).
[41] The electric field effects in $La_{2-x}Sr_xCuO_4$ are considered in P.

Konsin, Physica C **252**, 183 (1995).
[42] The ASYNNNI-type Hamiltonian in systems with asymmetrical hydrogen bonds was handled in random field approximation for explaining the ferroelectricity in these systems. See, for example, P. Konsin, Phys. Status Solidi B **70**, 451 (1975).
[43] V. Müller, C. Hucho, D. Maurer, K. D. de Groot, and K. H. Rieder, Physica B **165-166**, 1271 (1990).
[44] S. K. Kurtz, A. Bhabba, and L. E. Gross, Ferroelectrics **117**, 261 (1991).
[45] V. Müller, C. Hucho, and D. Maurer, Ferroelectrics **130**, 45 (1992).
[46] D. Mihailovic and I. Poberaj, Physica C **185-189**, 781 (1992).
[47] N. Kristoffel, Ferroelectrics **130**, 137 (1992).
[48] P. Konsin, N. Kristoffel, and T. Örd, Phys. Lett. A **129**, 339 (1988); **137**, 420 (1989); **143**, 83 (1990).
[49] P. Konsin and T. Örd, Physica C **191**, 469 (1992).
[50] N. Kristoffel, P. Konsin, and T. Örd, Riv. Nuovo Cimento **17**, 1 (1994).
[51] B. K. Chakraverty, Phys. Rev. B **48**, 4047 (1993).
[52] J. E. Hirsch and F. Marsiglio, Phys. Rev. B **43**, 424 (1991).
[53] R. Combescot and X. Leyronas, Phys. Rev. Lett. **75**, 3732 (1995); Phys. Rev. B **54**, 4320 (1996).
[54] M. Di Stasio, K. A. Müller, and L. Pietronero, Phys. Rev. Lett. **64**, 2827 (1990).
[55] J. B. Torrance, A. Bezinge, A. I. Nazzal, and S. S. Parkin, Physica C **162-164**, 291 (1989).
[56] C. N. R. Rao and A. K. Ganguli, Physica C **235-240**, 9 (1994).
[57] R. S. Markiewicz, J. Phys. Chem. Solids **58**, 1179 (1997).
[58] S. J. L. Billinge and T. Egami, Phys. Rev. B **47**, 14 386 (1993).
[59] J. L. Tallon, C. Bernhard, H. Shaked, R. L. Hitterman, and J. D. Jorgensen, Phys. Rev. B **51**, 12 911 (1995).
[60] Q. Li, X. X. Xi, X. D. Wu, A. Inam, S. Vadlamannati, W. L. McLean, T. Venkatesan, R. Ramesh, D. M. Hwang, J. A. Martinez, and L. Nazar, Phys. Rev. Lett. **64**, 3086 (1990).
[61] The photodoping in ferroelectrics leads to photoinduced phenomena. See, for example, P. J. Konsin and N. N. Kristoffel, Kristallografiya **17**, 712 (1972); V. M. Fridkin, *Ferroelectrics-Semiconductors* (Nauka, Moscow, 1976); *Photoferroelectrics* (Nauka, Moscow, 1979). For the vibronic theory of ferroelectricity see, for example, N. Kristoffel and P. Konsin, Ferroelectrics **6**, 3 (1973); **21**, 477 (1978); Phys. Status Solidi B **149**, 11 (1988); P. Konsin, *ibid.* **86**, 57 (1978).
[62] D. Mihailovic and J. Poberaj, J. Phys. Chem. Solids **54**, 1315 (1993).