Electrostatic interface tuning in correlated superconducting heterostructures

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An electrostatic field, which is applied to a gated high-temperature superconducting (HTSC) film, is believed to affect the film similar to charge doping. Analyzing the pairing in terms of a $t$–$J$ model, we show that a coupling to electric dipoles and phonons at the interface of film and dielectric gate localizes the injected charge and leads to a superconductor-insulator transition. This results in a dramatic modification of the doping dependent phase diagram close to and above the optimal doping which is expected to shed light on recent electric field-effect experiments with HTSC cuprates.

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I. INTRODUCTION

Interface physics of strongly correlated oxides is a rapidly developing branch of materials science. In heterostructures of ultrathin correlated oxide films, charge and spin states are reconstructed at the interfaces and hence affect the electronic properties of the entire system. This interface-controlled behavior provides new opportunities for oxide-film electronics, where a powerful tool for tuning the heterostructure properties is the electric field. In high-temperature superconducting oxides, electric fields can be used to switch between superconducting and insulating states by electrostatically tuning the free carrier density. In contrast to chemical doping, where the modifications in the doping level are inevitably related to changes in chemical bonding and microstructure, the field-effect experiments are expected to only modify charge, keeping the microstructure fixed.

In superconducting field-effect transistors (SuFET’s), an electric field is applied to a dielectric gate and sweeps charge carriers into a HTSC-film in the drain-source channel. The gate polarization attracts the injected carriers at the gate/film-interface. It thereby creates an accumulation region with a shifted local $T_c$ which, for a nm-thick film, should result in a tuning of the global $T_c$. With the assumption of a fixed interface microstructure, the field-induced $T_c$ shift should be fully determined by the electric field doping. However, whereas in underdoped HTSC cuprate films the observed $T_c$ shift is about 5–18 K, in the overdoped films $T_c$ is not substantially changed by the field. This striking doping dependence is usually explained in terms of a Thomas-Fermi screening length $\lambda_{TF}$ which suggests a stronger exponential decay of accumulated charge inside the overdoped films with higher total carrier density. However, in anisotropic systems, the quantum mechanically determined spread of the charge from the interface is greater and decays slower, in distinction to the classical Thomas-Fermi approach. As the cuprate films contain CuO$_2$-planes with an interplanar distance $\sim$ 1 nm, only a particular amount of injected charge is accumulated in the first plane at the interface, and the rest is redistributed in the 2–4 nearest planes. In these multilayers, the charge confinement to the first plane increases for higher total charge densities in the film. Consequently, in the underdoped cuprate film, despite larger $\lambda_{TF}$, the low carrier density results in $\sim$ 80% of confined charge (mechanisms to achieve stronger confinement have been studied in Ref. 3). In the overdoped film, about 100% of the injected charge is confined. As in both cases the calculated field-accumulated charge densities are roughly equal, one should expect similar shifts of $T_c$ both in the under- and overdoped films. This similarity implies that without consideration of the microscopic processes at the gate/film interface, the field doping alone cannot satisfactorily explain the doping dependences of the $T_c$ shift.

In a typical SuFET, the strong modulation of injected carriers requires a gate polarization in the range 10–30 $\mu$C/cm$^2$. To achieve this polarization, one uses gates with dielectric constant $\varepsilon$ in the range 20–100, fabricated from complex perovskite transition metal oxides like SrTiO$_3$ (STO). Here, extensive studies show that a fundamental property is the hybridization of oxygen (O) $p$- and transition metal (Ti) $d$-orbitals caused by the Ti-O-displacements. The Coulomb interaction $V_{pd}$ of a small amount of injected holes with the hybridized $p$-$d$ electrons in the insulating gate remains almost unscreened, $V_{pd} \sim 1–2$ eV—the spatial distance between the nearest interface unit cells of gate and film is about 2.5–5 Å. Moreover, the holes strongly interact with optical TiO-phonons which polarize the interface. These excitation processes at the interface can possibly lead to charge localization. A further reason for interface charge trapping can be an increased disorder at the cuprate/STO-interface which can lead to Anderson localization. In fact, interface localization is experimentally supported by a hysteresis of the normal state resistance and by the voltage dependence of the hole mobility in HTSC/STO heterostructures. There are also clear experimental indications that in organic field effect transistors, where a similar mechanism of the electric field effect applies, the carrier mobility decreases with increasing $\varepsilon$.

As a step towards an understanding of the cooperative interface phenomena in correlated oxides, we present a theoretical study of field-doped heterostructures, whereby we focus on two key aspects: (i) the interaction of the injected charge carriers with $p$-$d$-electrons in the dielectric gate, and (ii) the coupling of carriers to...
dynamical lattice distortions. We find that these processes at the gate/film interface result in dramatic modifications of the superconducting state with increasing field-induced carrier density.

II. MICROSCOPIC SCHEME OF THE ELECTRIC FIELD EFFECT

To analyze the field dependence of the p-d hybridization at the gate interface, we introduce a model on a 2D-square lattice containing $N_1$ sites, where each site corresponds to a perovskite unit cell. In each $O_6$-octahedron of the $i$-th cell we consider a single TiO ionic group with a dynamical covalent bond along the field direction perpendicular to the gate/film-interface (shown in Fig. 1). In this TiO group, we include only two states ($p$ and $d$) expressed by the operators $d_{i}^\dag (d_i)$ and $p_{i}^\dag (p_i)$ which obey the one-electron constraint $d_{i}^\dag d_i + p_{i}^\dag p_i = 1$. In a SuFET, the gate electric field $\varepsilon_g$ affects the p-d-electron transfer:

$$H_{pd} = \frac{1}{2} \Delta_{pd}^0 \sum_i (d_i^\dag d_i - p_i^\dag p_i) + E_{pd} \sum_i (p_i^\dag d_i + d_i^\dag p_i). \quad (1)$$

The energy gap $\Delta_{pd}^0$, is about 3 eV in perovskite dielectric states, but decreases down to 1.5 eV in ferroelectric films due to modifications of surface electronic states.

The electrostatic interaction $E_{pd} = \varepsilon_g d_{pd}$ of the gate field with the dipole moment, $d_{pd} = e r_{pd}$, of the electron transfer increases the p-d level splitting and thus tends to localize the TiO-electron. Here $e$ is the electron charge and $r_{pd} \approx 2$ Å is the Ti-O distance. The energy gap $\Delta_{pd}^0$ in (1) refers to $\varepsilon_g = 0$. In a nonzero electric field, which induces a polarization $P_z \sim \varepsilon_g$, the field-dependent TiO-distortions $u_i \sim P_z$ imply $\Delta_{pd}^\varepsilon = \Delta_{pd}^0 + \chi_e u_i$. The field effect can be taken into account via the expansion of $\Delta_{pd}^\varepsilon$ in powers of $P_z$: $\Delta_{pd}^\varepsilon = \Delta_{pd}^0 (P_z^0 + \frac{\partial \Delta_{pd}^0}{\partial P_z} \varepsilon_g)$, which determines the "susceptibility" $\chi_e \sim \frac{\partial \Delta_{pd}^0}{\partial P_z} \frac{\partial \varepsilon_g}{\partial P_z}$. In thin STO films, the high concentration of oxygen vacancies leads to local polar regions and to a quasistatic polarization $P_z^0 \neq 0$. The additional, maximal electric field-induced polarization is comparable to $P_z^0$ and the influence of $\varepsilon_g$ on $P_z$ is relatively weak compared to the effect produced by the polar regions. Therefore, for the considered range of $\varepsilon_g < 10^5$ V/cm, we have $\chi_e \varepsilon_g \ll P_z^0$ and consequently we take $\Delta_{pd}^\varepsilon = \Delta_{pd}^0$ in (1).

Furthermore, we assume that the barrier for a p-d-transfer (described by the second term in (1)) is modified by the interface coupling to the carriers in the superconducting film

$$H_{exc} = V_{pd} \sum_{i\sigma} (1 - n_{i\sigma}) (p_i^\dag d_i + d_i^\dag p_i). \quad (2)$$

We consider in (2) the coupling with holes, where $n_{i\sigma}$ is the electron number operator with spin $\sigma$, and $n_i = \sum_{\sigma} n_{i\sigma}$. The mechanism (2) can lead to a local effective attraction between the injected carriers, which has recently been analyzed for weak-coupling s-wave superconductors.

The role of the TiO-distortions is more subtle. As shown in Ref. [10] the coupling of the injected charge to a static displacement only shifts the chemical potential in the film. Consequently, we neglect the coupling to static distortions and we focus instead on dynamical TiO-displacements. We are interested in the coupling to the low-energy soft TO$_1$-mode, the polar component of which is hardened up to 50-80 cm$^{-1}$ at low $T$ in STO thin films in electric fields. Also, we consider higher-energy polar phonons like the TO$_2$- (170 cm$^{-1}$) or the TO$_4$-mode (545 cm$^{-1}$). At the gate/film-interface, such TiO-displacements are coupled to the holes in the film

$$H_{pol} = \hbar \omega_{TO} \sum_i b_i^\dagger b_i - \gamma_0 \sum_i (1 - n_i)(b_i^\dagger + b_i), \quad (3)$$

where the phonon operators $b_i^\dagger (b_i)$ refer to a particular TiO-mode of energy $\omega_{TO}$, $\gamma_0 = \sqrt{\hbar \omega_{TO} E_p}$ is the hole-phonon coupling, and $E_p$ is the polaron binding energy.

In the superconducting film, we focus only on the first plane (ideal confinement) without detailed analysis of the interplanar charge redistribution. We treat the film in terms of a 2D-Hubbard model which contains on-site correlations with a nearest and next-nearest tight-binding
dispersion $\varepsilon_k = -2t(\cos k_x + \cos k_y) - 4t' \cos k_x \cos k_y$:

$$H_{\text{film}} = \sum_{k\sigma} \varepsilon_k c_{k\sigma}^\dagger c_{k\sigma} + U \sum_i n_i^\uparrow n_i^\downarrow,$$  \hspace{1cm} (4)

where $c_{k\sigma}^\dagger$ are electron creation operators. We choose the typical values $t' / t = -0.3$ and $U = 8t$. For the doped Cu 3$d$ band, the effective Hamiltonian describes the motion of hole singlets through the lattice of Cu$^{2+}$-ions in CuO$_2$-planes. These spin singlets are formed by the Cu hole and the O hole of the O-plaquette which is hybridized with the d-states of Cu$^{2+}$ ions.

The combined model now presents a field-driven two-layer interface system in which the strongly correlated charge carriers in the film are coupled to TiO-excitons and to phonon states of the gate. Figure 1 shows a possible bonding at a CuO$_2$/STO-interface. Here the oxygen ion is located between Ti$^{4+}$ and Cu$^{2+}$ forming a TiO-Cu bond with the shortest distance between Cu (film) and O (STO-gate) as compared to other possible chemical bonding configurations which can appear in HTSC/STO-heterostructures. The coupling between the Cu holes and TiO-excitations results in a renormalization of the CuO-hybridization amplitude $t_{\text{CuO}}$ in the planar CuO-squares and, consequently, in a renormalization of the effective hole hopping parameters $t = t_{\text{CuO}}^2 / \varepsilon_p^O$ ($\varepsilon_p^O$ is the energy of the planar O p-state) and $t'$. In addition, in the configuration shown in Fig. 1 we also obtain an attractive correction to the one-site repulsion $U$. To analyze the resulting electronic parameters in the film, we first derive an effective Hubbard model by tracing over phonon and exciton degrees of freedom and therefore replace the site-dependent parameters by their averages: $u_i = u, N_{\text{pol}}^{-1} \sum_{\sigma} \langle n_i^\sigma \rangle = 1 - x$. In the effective Hamiltonian $H_{\text{film}}$, the hopping energies $t$ and $t'$ are reduced by the polaron band narrowing factor $\xi_{\text{pol}}(\eta) = \exp[-\eta^2 E_p / \hbar \omega_{\text{TO}} \cosh \frac{1}{2} \lambda \hbar \omega_{\text{TO}}]$ where $\tau = \exp(-4\alpha)$. The parameters $u, \xi$ and $\eta$ are determined by minimization of $\langle U^1 \rangle (H_{\text{pol}} + H_{\text{film}} - U_{\text{pol}})$, which is averaged over the phonon vacuum. In particular, for $\eta$ we have the following self-consistent equation:

$$\eta = 1 / \left[ 1 - (\tau / \hbar \omega_{\text{TO}}) e_K(x) \xi_{\text{pol}} \right],$$  \hspace{1cm} (5)

where $e_K(x) \approx -2(t + t')(1 - x)$ is obtained from the average kinetic energy in $H_{\text{film}}$, which controls the dependence of $\eta$ on $x$. For low $x$, the contribution of $e_K$ to the denominator in (5) is significant which results in small $\eta$ and weak polaron band narrowing $\xi_{\text{pol}}(\eta)$. On the other hand, when the hole-phonon coupling is strong and $x$ increases, $\eta$ approaches 1, which leads to a localization of holes. This signifies that the reduced kinetic energy at sufficient concentration of holes triggers the polaronic localization transition. Consequently, the exchange energy $J_{\text{eff}}$ which is controlled by $t_{\text{eff}} = t_{\text{pol}} \xi_{\text{pol}}$, is drastically suppressed (Fig. 2). For the soft TiO-mode (Fig. 2(a)), a suppression of $J_{\text{eff}}$ is obtained for $E_p / t > 1$

III. COOPERATIVE p-d-EXCITON & POLARON EFFECT

We investigate first the TiO hybridization. To eliminate first order coupling terms in $V_{pd}$, we apply the unitary transformation $U_{\text{exc}} = \exp[-\zeta_{pd} \sum_{i} s_i^p n_i^\sigma]$ to $H_{pd} + H_{\text{exc}} + H_{\text{film}}$ with $s_i^p = i(d_i^\dagger p_i - p_i^\dagger d_i)$, $\zeta_{pd} = V_{pd} \Delta_{pd}^0 / 4(\Delta_{pd}^2 + 2 V_{pd} E_{pd})$ and $\Delta_{pd} = \sqrt{E_{pd}^2 + (\Delta_{pd}^0 / 2)^2}$. Averaging the obtained expansion over p-d-exciton states, we find a reduction of the electron hopping parameters $t$ and $t'$ by the factor $\zeta_{pd} = \cos^2 \zeta_{pd}$. For the considered range of $V_{pd}$, the attractive corrections $\Delta U_{pd}$ to $U$ are small, $\Delta U_{pd} / U \sim 0.2$, and result in a maximal increase of $J_{\text{eff}} / J \sim 1.07$. Consequently, in distinction to weak-coupling superconductors, this contribution of the p-d transfer to the increase of $T_c$ is insignificant. In contrast, a pronounced renormalization of $J_{\text{eff}}$ originates from the kinetic term $t_{\text{eff}} = t_{\text{pol}} \xi_{pd}$. For $V_{pd} / \Delta_{pd}^0 \sim 1$, we find that $t_{\text{eff}} / t$ can be reduced by $\xi_{pd}$ down to $\sim 0.7$. On the other hand, the application of an electric field enhances the exciton factor $\xi_{pd} \to 1$ and hence counteracts polaron localization. This may cause a field-tuned delocalization of holes in the film when we take into account both, p-d-transfer and TiO-phonons.

The electron-phonon coupling in $H_{\text{pol}}$ results in a polaron effect at the gate/film-interface. With the soft phonon mode, the typical values for the interface coupling $\gamma_0 \sim 0.01$–0.1 eV imply large polaronic energies $E_p / \hbar \omega_{\text{TO}} \sim 0.1$–5, where the TiO-mode energy $\hbar \omega_{\text{TO}} / t \sim 10^{-2}$–$10^{-1}$ ($t \approx 0.25$ eV) can be close to the adiabatic limit. To diagonalize (4), we apply a variational Lang-Firsov transformation $U_{\text{pol}}(u, \alpha, \eta)$. The variational parameter $\eta$ describes the strength of the polaron effect, $u_i$ presents interface static distortions, and $\alpha$ allows for anharmonic excitations. We assume homogeneity in the low-temperature state of the doped film and therefore replaced the site-dependent parameters by their averages: $u_i = u, N_{\text{pol}}^{-1} \sum_{\sigma} \langle n_i^\sigma \rangle = 1 - x$. In the electronic Hamiltonian $H_{\text{film}}$, the hopping energies $t$ and $t'$ are reduced by the polaron band narrowing factor $\xi_{\text{pol}}(\eta) = \exp[-\eta^2 E_p / \hbar \omega_{\text{TO}} \cosh \frac{1}{2} \lambda \hbar \omega_{\text{TO}}]$ where $\tau = \exp(-4\alpha)$. The parameters $u, \xi$ and $\eta$ are determined by minimization of $\langle U^1 \rangle (H_{\text{pol}} + H_{\text{film}} - U_{\text{pol}})$, which is averaged over the phonon vacuum. In particular, for $\eta$ we have the following self-consistent equation:

$$\eta = 1 / \left[ 1 - (\tau / \hbar \omega_{\text{TO}}) e_K(x) \xi_{\text{pol}} \right],$$  \hspace{1cm} (5)

where $e_K(x) \approx -2(t + t')(1 - x)$ is obtained from the average kinetic energy in $H_{\text{film}}$, which controls the dependence of $\eta$ on $x$. For low $x$, the contribution of $e_K$ to the denominator in (5) is significant which results in small $\eta$ and weak polaron band narrowing $\xi_{\text{pol}}(\eta)$. On the other hand, when the hole-phonon coupling is strong and $x$ increases, $\eta$ approaches 1, which leads to a localization of holes. This signifies that the reduced kinetic energy at sufficient concentration of holes triggers the polaronic localization transition. Consequently, the exchange energy $J_{\text{eff}}$ which is controlled by $t_{\text{eff}} = t_{\text{pol}} \xi_{\text{pol}}$, is drastically suppressed (Fig. 2). For the soft TiO-mode (Fig. 2(a)), a suppression of $J_{\text{eff}}$ is obtained for $E_p / t > 1$

![FIG. 2: Effective exchange energy $J_{\text{eff}}$ vs hole doping $x$ for $\Delta_{pd} / At = 3.0$, $V_{pd} / At = 0.5$, $\varepsilon_0 = 0$, and different polaron energies $E_p$ (in units of $t$) in the case of coupling to (a) a soft mode $\hbar \omega_{\text{TO}} / t = 0.05$; (b) a high-energy mode $\hbar \omega_{\text{TO}} / t = 0.4$.](image-url)
in the relevant range \( x < 0.3 \). Coupling instead to the high-energy mode (Fig. 2(b)) increases the minimal values of \( E_p \) required for the localization, and therefore the suppression of \( J_{\text{eff}} \) is substantially weaker.

IV. SUPERCONDUCTIVITY IN THE FILM

For our considerations it is important that for all widely discussed concepts of high-\( T_c \) superconductivity, a suppression of \( J_{\text{eff}} \) is feasible due to the loss of the kinetic energy by interface localization. This suppression may in fact result in lower pseudogap temperature \( T^* \sim J_{\text{eff}} \) and critical temperature \( T_c \). In order to relate our findings to a distinct model, we approach the superconductivity in the strongly correlated electronic system within a slave-boson approach\(^\text{10} \). In this scheme spin-carrying fermions \( f_{i\sigma} \) and spinless bosons \( h_i \) are introduced through \( c_{i\sigma} = f_{i\sigma}^\dagger h_i \) whereby the constraint \( \sum_{\sigma} f_{i\sigma}^\dagger f_{i\sigma} + h_i^\dagger h_i = 1 \) is to be enforced. We consider the pairing \( \Delta_{ij} = \langle f_{i\sigma} f_{j\bar{\sigma}} - f_{i\bar{\sigma}} f_{j\sigma} \rangle \), bond \( \chi_{ij} = \langle f_{i\sigma}^\dagger f_{j\bar{\sigma}} \rangle \) and boson condensation \( \kappa = \langle h_i \rangle^2 \) order parameters. With the mean-field factorization of the \( t-J \) Hamiltonian, focusing on the uniform solutions \( \Delta_{ij} = (-1)^{\delta_{ij} + j} \Delta_d \), \( \chi_{ij} = \chi \), we obtain a free energy, which is to be minimized with respect to \( \Delta_d \), \( \chi \), \( \kappa \). The system of selfconsistent equations for the order parameters has been solved numerically. The pairing amplitude \( \Delta_d \) determines the temperature \( T_{\text{RVB}} \), whereas the boson temperature \( T_{\text{BC}} \) has been estimated according to\(^\text{10,20} \) from the kinetic energy of the boson pairs assuming a weak \( t_1/t = 10^{-4} \) interplanar coupling in the film. The results are shown in the form of \( (T, x) \)-phase diagrams in Fig. 3 for different values of the polaron energy \( E_p \), where \( T_c \) corresponds to the lowest temperature among \( T_{\text{RVB}} \) and \( T_{\text{BC}} \). In Fig. 3 the gate field is \( \varepsilon_g = 0 \), and the standard phase diagrams are modified essentially due to the interface coupling with the soft mode. Here, at low doping \( x < 0.12 \), the superconducting region is limited by \( T_{\text{BC}} \), and for larger \( x \) by \( T_{\text{RVB}} \). The increase of the polaron energy \( E_p \) first affects the overdoped region where the right boundary of the superconducting phase is shifted from \( x_m \approx 0.3 \) to 0.17 as \( E_p/t \) increases to 1.2. With a further increase of \( E_p \), the collapse of \( T_{\text{RVB}} \) limits the superconducting state also in the underdoped region: the maximally achievable doping, \( x_m \), for superconductivity to prevail is \( x_m = 0.1 \) for \( E_p/t = 1.3 \), already below “optimal doping”. This is in striking contrast to the classical HTSC-behavior where \( T_c \) decreases due to the strong mode excitations in the gate. Note that for a film containing more than one superconducting plane, the suppression of pairing is incomplete\(^\text{21} \).

For the field tuned heterostructures, field-dependent phase diagrams are required. Fig. 4 shows the evolution of such a phase diagram with the increase of the interface polaron energy \( E_p \). The hole doping \( x(\varepsilon_g) \) measures the density of holes injected by \( \varepsilon_g \) into the film which is initially in the insulating \((x_0 = 0, \text{Fig. 4(a)})\) or in the superconducting \((x_0 = 0.15, \text{Fig. 4(b)})\) state. Here, \( x(\varepsilon_g) = Q/N_d \) with the charge \( Q = CV \), the dielectric capacitance \( C = \varepsilon_0 \varepsilon_r N_d a^2/d \), the lattice constant \( a \), the thickness of the dielectric film \( d \), and the bias voltage \( V = \varepsilon_g d \). For \( x_0 = 0 \), the maximally achievable field \( \varepsilon_g \approx 10^6 \) V/cm for a gate with \( \varepsilon = 100 \) allows to attain a doping of \( x \approx 0.13 \), which still is in the underdoped range (Fig. 4(a)). The decrease of \( J_{\text{eff}} \) for larger \( E_p \) leads to the suppression of both \( T_{\text{BC}} \) and \( T_{\text{RVB}} \). These temperatures also remain strongly dependent on \( \varepsilon_g \). In contrast, for \( x_0 = 0.15 \), when doping \( x(\varepsilon_g) \) is raised into the overdoped range, the increase of the polaron energy \( E_p \) not merely suppresses \( T_{\text{RVB}} \) (which limits the superconducting region), but also reduces the slope of \( T_{\text{RVB}} \) with respect to \( x(\varepsilon_g) \). The latter effect results in a decrease of the \( T_c \) shift, \( \Delta T_c = T_{\text{RVB}}(x_0 + \Delta x(\varepsilon_g)) - T_{\text{RVB}}(x_0) \), where the field \( \varepsilon_g \) injects the hole density \( \Delta g < 0.03 \) into the film. The corresponding shifts are presented in Fig. 4 and show a strong decrease of \( \Delta T_c \) for \( E_p/t > 1.2 \) in the overdoped range, whereas in the underdoped films \( \Delta T_c \) decreases but remains finite. This result supports

![FIG. 3: Phase diagram for d-wave superconductivity (shaded area) for three distinct polaron energies. Here \( J/t = 0.5 \), \( V_{pd}/4t = 1.0 \), \( \Delta_{pd}/4t = 3.0 \), and \( \hbar \omega_{TO}/t = 0.05 \).](image-url)

![FIG. 4: Field-dependent doping \( x(\varepsilon_g) \) raised from initial values (a) \( x_0 = 0 \) and (b) \( x_0 = 0.15 \): phase diagrams for d-wave superconductivity for different polaronic energies \( E_p \); \( V_{pd}/4t = 1.0 \), \( \Delta_{pd}/4t = 3.0 \), and \( \hbar \omega_{TO}/t = 0.4 \).](image-url)
the surprising fact that the field does not substantially change $T_c$ in the overdoped films.

The hole localization, which is also supported by experiments, presents a serious challenge to current attempts to induce superconductivity in the strongly correlated films. However, a possible recipe how to delocalize the holes follows from the analysis of the coupling between the CuO hole and $p$-$d$-TiO exciton. It was noted before that $\varepsilon_g$ increases the exciton factor $\xi_{pd}$ and enhances the hole motion for sufficiently large exciton-hole interaction $V_{pd}$. To analyze this effect, we investigate the region $x_0 = 0.13$–0.14 close to the transition into the localized state where superconductivity is already suppressed, and then apply the field. Due to the enhancement of $t_{eff}$ by $\xi_{pd}(\varepsilon_g)$, for $x_0 = 0.14$ we find a reentrant transition (Fig. 6) into the superconducting state. With the injection of more holes by $\varepsilon_g$, the kinetic term in (5) is reduced which leads to a second suppression of superconductivity at $x \approx 0.17$. For $V_{pd} \approx \Delta_{pd}^0$, the reentrant superconductivity is stable in a very narrow doping range (see Fig. 6). For $V_{pd} > \Delta_{pd}^0$, this range rapidly extends over the full overdoped regime $x \leq 0.3$. Such a strong $V_{pd}$, required for the hole delocalization, can be obtained in designed heterostructures with the holes in close proximity to the $p$-$d$ TiO-orbitals where Cu-states share an apical oxygen with the adjacent Ti as shown in Fig. 6. Alternatively, we propose to use multilayered cuprates with 3–5 CuO$_2$-planes in a unit cell to delocalize the holes. Due to the small interplanar distance of $\sim 3.2$ Å in some compounds, the polaron-suppressed hopping in the interface plane is in turn enhanced by the interplanar coupling to the subsequent planes.

We found that the cooperative effect of interface hybridization and lattice dynamics in strongly correlated superconducting heterostructures is of crucial importance to their superconducting properties. The interface-caused suppression of $T_c$ for higher doping is a possible explanation of the differences in the electric field effect in overdoped and underdoped SuFETs. The highly non-trivial behavior of $T_c$ under a variation of the field allows to propose mechanisms for charge delocalization which is a subject of further experimental and theoretical studies.

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21 In an extended description of the film, more CuO$_2$-planes should be coupled by interplanar electron tunneling. This effectively leads to a reduction of phonon-induced localization of holes resulting in a suppressed but finite $T_c$ for larger $x$. 
