Superconductivity Controlled by Polarization in Field-Effect Devices of Confined Geometry

Natalia Pavlenko$^{1,2}$ and Franz Schwabl$^1$

$^1$Institut für Theoretische Physik T34, Physik-Department der TU München, James-Franck-Strasse, D-85747 Garching b. München, Germany

$^2$Institute of Physics, University of Augsburg, 86135 Augsburg, Germany

We propose a concept for superconducting electric field-effect devices based on superconducting films sandwiched between ferroelectric layers. We provide theoretical calculations that indicate how the field effect in these devices could be amplified, which can be experimentally probed even at the current stage of film fabrication techniques.

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The electric field effect in superconductors attracts considerable attention in science and technology. The external field can modulate the charge density and resistance, and control a reversible superconductor-insulator switching behavior, which plays a key role in superconducting field-effect transistors (SuFETs) based on dielectric or ferroelectric polarisation. Especially in high-temperature superconducting oxides, where the low carrier density $n \sim 10^{21}$ cm$^{-3}$ yields larger electric penetration depths $\lambda_{TF} \sim 1$ nm, a switch of the ferroelectric polarization is found to produce $\sim 10\%$ modulation in the carrier density $n$ at the interface. The observed changes in $n$ and in the superfluid density $n_S$ are shown to be the key factor responsible for a several K shift of the superconducting transition temperature $T_c$ in the underdoping region where $T_c$ is proportional to $n_S(0)$.

In the superconducting films of a thickness $\gg \lambda_{TF}$, the shift of $T_c$ due to the charge modulation in the interface region of about 1 nm thickness is shunted. Thus, it is especially advantageous for SuFETs to use ultrathin superconducting channels of a few nm thickness.

To make such SuFETs suitable for technological applications, the achievement of $T_c$ shifts beyond the range $5-10$ K is required. This needs the mechanisms of a possibly stronger charge density modulation by the gate polarization in the range 10-30 $\mu$C cm$^{-2}$ which is currently achievable in ferroelectric oxides Pb(Zr,Ti)O$_3$ (PZT) and (Ba,Sr)TiO$_3$ (BSTO).

Recently, theoretical studies of superconducting-ferroelectric (S-FE) multilayers have shown that the modulation of charge in the ultrathin superconducting films sandwiched between the ferroelectric layers is much stronger than in ferroelectric-superconductor bilayers typically exploited for SuFETs. In a sandwich-like FE$_1$-S-FE$_2$ heterostructure (Fig. 1(a)), the polarization $P_2$ in the second gate FE$_2$ pushes an extra charge from the interface S-FE$_2$ into the accumulation region at the interface FE$_1$-S of the S-film. For high-$T_c$ cuprates as the most compatible candidates for the sandwiches, the redistribution of carriers between the interfaces driven by $P_1$ and $P_2$ could require S-films of 2-3 unit cell thickness.

In such films, the charge redistribution between CuO$_2$-planes can occur via the interplanar tunneling of Cooper pairs which provides not only the way for the charge modulation, but also enhances the local $T_c$ in the entire S-film. For possible realizations of SuFETs based on FE-S-FE sandwiches, the question that needs to be addressed is how the superconducting properties can be controlled by the voltages in FE-gates which is the subject of present studies.

Here we consider a superconducting film containing $L_S = 2$ or 3 infinite 2D-planes, as shown in Fig. 1(a) for $L_S = 2$. The superconductivity in each plane is described by a BCS-like model with an effective pairing potential $V^0$ (except that the energy cutoff is determined by the electron bandwidth). These planes are weakly connected by the interplanar Cooper pair tunneling with the tunneling energy $t_\perp/t = 0.05-0.1$ ($t \approx 0.1$ eV for high-$T_c$ cuprates) is the nearest neighbor hopping energy on a square lattice, which sets the energy scale). The S-film is sandwiched between the FE-layers of a thickness given by the number $L_F$ of unit cells in $z$-direction perpendicular to the interfaces. In SuFETs, the charge redistribution in the S-film can be achieved by reorienting the polarizations $P_1$ and $P_2$ in the layers FE$_1$ and FE$_2$ perpendicular to the interfaces by the gate electric field $E_g^1$ and $E_g^2$. Hence, we focus essentially on the two possible orientations of ferroelectric dipoles (one of them is shown in Fig. 1(b)), representing them by two values $\pm 1/2$ of a pseudospin (dipole) operator. To describe by this pseudospin formalism the nonzero spontaneous polarization in each FE-layer due to ion displacements below the Curie temperature, we employ an Ising model with the dipole-dipole interaction energy $J_F$ taken into account in addition to the interactions $-E_{g1}^1 \cdot P_1$ and $-E_{g2}^2 \cdot P_2$ with the gate fields $E_g$. The screening of the polarization at the interfaces by the charge in the S-film is described by the electrostatic charge-ferroelectric dipole interaction $\gamma = \Delta_{SF} \cdot d_{FE}$. Here $d_{FE}$ is the magnitude of the dipole in each FE-unit cell and $\Delta_{SF}$ is the distance between the nearest FE-unit cell and S-film. In our analysis, the in
ferface energy $\gamma$ ranges from zero (isolated S-film) to $\sim t$, which should lie in a typical range of the charge-dipole interactions at the contacts with ferroelectric BSTO(PZT)-layers of $\sim 100-300$ Å thickness where the polarization $\lesssim 25\mu$ C cm$^{-2}$ is suppressed due to strong depolarization fields $\mathbf{S}$. We study the system far below the Curie temperature, treating the ferroelectric polarization in the mean-field approach $\gamma_{\mathbf{S}}$. Then the superconducting temperature, treating the ferroelectric polarization in the depletion region without affecting the final distribution of the injected charge $(n_1 = n_2 = n)$ which results in the constant $T_c$ in Fig. 1(b).

Based on these advantages of sandwiches, we propose that the operation of an SuFET containing an S-film confined between two FE-layers, can be realized in two steps which are shown in two possible realizations in Fig. 2(a) and (b). Here, step(1) switches the SuFET to the superconducting state with the enhanced $T_c$ caused by the parallel polarization in the FE-gates. This can be achieved by applying the voltages $V_g$ to the gate electrode $FE_1$ and $-V_g$ to $FE_2$. In the first realization of step(1)(Fig. 2(a)), the power supply simultaneously moves the opposite charge to the gate electrodes. To reset the SuFET to the state with lower $T_c$ (step(2)), one destroys the accumulation layer at the $FE_1$-S contact, which is realized here by decreasing the gate voltages $V_g$ and tuning the gate polarization to zero. However, with the gates fabricated from the PZT(BTO)-compounds, a nonzero spontaneous polarization $P_s \neq 0$ at $V_g = 0$ could result only in a partially removed accumulation region.

Thus, in this realization we propose to use the gates made with STO or BSTO with high Sr content, so that $P_s \approx 0$ at temperatures close to $T_c$. The corresponding modulation of $T_c$ is illustrated in Fig. 2(a) for the $s$- and $d$-wave pairing in the superconducting channel. As compared to the FE-S-bilayers and $s$-symmetry channels, the remarkable shift of $T_c$ in step(1) is obtained for the $d$-wave sandwiches, which strongly supports the use of high-$T_c$ cuprates in the proposed SuFETs. For a more realistic analysis of $d$-wave pairing, we choose the band structure with the next-nearest-neighbor hopping which resembles the Fermi surface of YBa$_2$Cu$_3$O$_{7-\delta}$. The electron density is taken near half-filling, where the cases $n = 0.9$ (hole density $x = 1 - n = 0.1$) and $n = 0.75$ ($x = 0.25$) should correspond to the under- and overdoped regions. There are a few important points to note. First, for underdoping, the obtained increase of $T_c$ is stronger than that for overdoping, which agrees well with the recent observations of the strong field-effect in the underdoped region of the cuprate phase diagram $\mathbf{2}$. Second, as the present studies are based on a BCS-type model, the obtained here estimates for the $T_c$ increase in the underdoped region consider only the mean-field boundary for the transition temperature. To get more precise estimates for underdoping, the lowering of $T_c$ by phase fluctuations $\mathbf{4}$ should be analyzed, which is the object of future studies.

In the second realization (Fig. 2(b)), the electric power sweeps the charge from the $FE_1$-gate electrode and injects it into the S-channel. Here, the $FE_2$-polarization is used to control the additional enhancement of $T_c$ in the channel. Reversing the $FE_2$-polarization switches the SuFET into the antiparallel polarization state with the lower $T_c$. The modulation of $T_c$ by a change of the $FE_2$-gate field for the fixed $FE_1$-gate field is shown in Fig. 2(b), where the strong increase of $T_c$ in a $d$-wave conducting channel is obtained when going from the step
Another possible modification of the second realization could include the injection of additional charge from the FE$_2$-gate electrode into the channel and thus achievement of higher $n$ (or $x$) in the state with antiparallel polarization. Although the charge densities in both accumulation planes in this case are comparable to those with the parallel $P$, the question of the inter-planar charge modulation and thickness dependence of $T_c$ needs further theoretical studies.

In conclusion, we have discussed the schemes of SuFETs based on ferroelectric-superconducting sandwiches, where the $d$-wave channels show great potential for strong modulation of $T_c$. However, for a successful implementation, important theoretical and technological issues (related to the the growth of good quality interfaces where the interface steps do not significantly affect the charge redistribution in S-film) need to be solved.

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![FIG. 1](image1)

**FIG. 1:** (a) Scheme of FE-S-FE sandwich with the uniform parallel spontaneous polarization in FE-layers. (b) $T_c$ vs $\gamma$ in sandwiches containing $L_F=10$ FE-monolayers, where the cases of parallel and antiparallel gate polarization are shown for a comparison. Here $V^0/Y = -3.5$, $J_F/t = 1$, $t_c/t = 0.1$, and the electronic band filling $n = 0.3$. All the temperatures are scaled by $T_c(\gamma = 0, L_S = 2)$, and we show here the case of s-wave pairing in S-film.

![FIG. 2](image2)

**FIG. 2:** Proposed schemes of SuFET based on confined FE-S-FE geometry. In step(1) with parallel gate polarization the SuFET is in the state with enhanced $T_c$, whereas step(2) destroys (a) or decreases (b) the electron accumulation at FE$_1$-S interface and thus switches SuFET into the state with low $T_c$.

![FIG. 3](image3)

**FIG. 3:** Superconducting transition temperature under variation of gate electric fields (a) for scheme shown in Fig.2(a) where the gate fields $E_g^0 = E_{sd}^0 = E_{g}^0$ set the parallel polarization in both STO-gates of thickness $d=300$ nm with the dielectric constant $\varepsilon = 100$ and maximal achievable polarization $P_{max} = 5\mu C cm^{-2}$; (b) for scheme shown in Fig.2(b) where the FE$_1$-gate field is fixed whereas the FE$_2$-gate field is switched resulting in a reverse of the FE$_2$-polarization at the coercive field $E_c$ in step (2). Here $\gamma/t = 0.5$ and FE-layers with a polarization $P_S = 30\mu C cm^{-2}$ are considered. In S-film for $d$-wave pairing, the planar band structure $\varepsilon_k = -2t(\cos k_x + \cos k_y) - 4t_2\cos k_x\cos k_y$ is chosen with next-nearest-neighbor hopping $t_2/t = -0.4$, $t_c/t = 0.05$ and $V^{0}/Y = -0.5$. All gate fields are scaled by a characteristic maximum field $E_g^{0} \approx 10^6 V/cm$.

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[*] Electronic mail: pavlenko@mailaps.org

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