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Electric Field Effect in High-T_c Superconductors

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Abstract

A brief summary of electric field effects on the normal and the superconducting state of high-T_c superconductors is given. Novel experiments are presented in which electric fields are used to modulate the transport properties of weak links. Analogies between the effects of electric and magnetic fields on superconductivity are emphasized.

1. Introduction

Since the beginning of the 1960's there has been an ongoing effort to use electric fields to control the transport properties of superconducting films [1-5]. These activities were extended both experimentally and theoretically to the high-T_c cuprates shortly after the discovery of these materials [6-14] because they are exceptionally well suited for field effect studies. Their relatively low carrier density n in conjunction with a sizable dielectric constant ε_r^{sc} results in relatively large electric penetration depths λ^{el}. Furthermore, their small coherence lengths ξ allow the fabrication of ultrathin superconducting films in which the total carrier density can be modulated to a substantial extent. These properties are not only helpful from a technological perspective, but are also essential for the field effect from a fundamental point of view [15,16]. If a superconductor is penetrated by an electric field, its response to the field will depend sensitively on the value of the parameter ι

$$\iota(T) := \frac{\lambda_z^{el}(T)}{\xi_z(T)} \quad ,$$

where $\lambda_z^{el}(T)$ is the temperature-dependent electrical penetration depth and $\xi_z(T)$ is the coherence length in field direction. Comparable to the Ginzburg-Landau parameter κ, which classifies the response of a superconductor to applied magnetic fields, the parameter ι classifies the response of a superconductor to electric fields by differentiating between $\iota < 1$ and $\iota > 1$ superconductors. In both cases the field is shielded approximately exponentially from the interior of the superconductor, with the shielding length given by λ_z^{el}. Thus, the thickness of the layer in which the carrier density can be modulated is of the order of λ_z^{el}. For superconductors with $\iota < 1$, however, the superconducting properties are controlled by a layer of thickness ξ_z and will thus barely respond to the field. If $\iota > 1$, the coherence length ξ_z is small enough for the superconducting order parameter to adjust to the modified carrier density. Therefore, in superconductors with $\iota > 1$ the superconducting properties of the field penetrated layer can be altered sensitively by the applied field.

Remarkably, standard low-T_c superconductors are small ι superconductors. For niobium at 4.2 K, for instance, $\iota \approx 3 \times 10^{-3}$, as $\lambda_{el} < 1$ Å and $\xi(4.2\ K) \approx 380$ Å. In the high-T_c cuprates, however, both λ_z^{el} and ξ_z equal a few angstroms, thus $\iota \approx 1$. This is the basis of the large electric field effects in the high-T_c cuprates.

In this contribution field effect experiments performed with $YBa_2Cu_3O_{7-\delta}$ films at the IBM Zurich Research Laboratory shall be discussed. For reviews of work performed by other groups the reader is referred to Refs. 16 and 17. After an introduction to sample preparation, the effect of electrostatic fields on the normal state transport, on T_c, and on the superconducting state will be presented. A separate chapter is devoted to the influence of applied electric fields on the transport properties of weak links in high-T_c superconductors. For weakly linked samples, shifts of T_{c0} of more than 10 K are reported. By way of summary, analogies between the roles of magnetic and electric fields in superconductors will be considered.

2. Sample Preparation and Measurement Technique

The standard sample configuration used in the experiments is shown in Fig. 1 [18]. An n-type {100}-oriented 0.05% Nb-doped $SrTiO_3$ single crystal grown with the zone-melting technique [19] is used as the substrate and gate electrode. As a thin insulating surface layer, which is detrimental to sample performance, forms on the surface of such crystals, 1-5 nm thin Pt films were grown on the doped $SrTiO_3$ by

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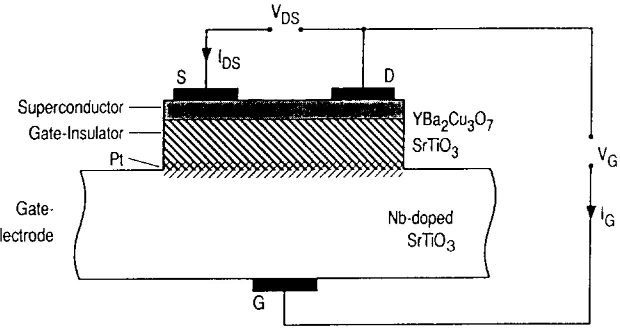

Fig. 1: Standard sample configuration used for the study of field effects. From [11].

electron beam evaporation. On top of the Pt layer, {100}-oriented and highly insulating layers of $SrTiO_3$ were epitaxially deposited by reactive rf-magnetron sputtering at 0.05 Torr in an O_2/Ar atmosphere at ≈650 °C (temperature of the sample holder). $SrTiO_3$ was chosen as the material for the gate barrier because it is compatible in growth with $YBa_2Cu_3O_{7-\delta}$ and it offers high dielectric constants without becoming ferroelectric at low temperatures where it is in a quantum paraelectric state [20]. Finally, $YBa_2Cu_3O_{7-\delta}$ films were sputter deposited with a hollow cathode magnetron. Contacts were made to the $YBa_2Cu_3O_{7-\delta}$ layer by sputtered Au pads and to the conducting substrate by diffusing silver into the Nb-doped $SrTiO_3$. To avoid leakage through pinholes, relatively thick (≈500 nm) insulating $SrTiO_3$ layers were used, whereas the $YBa_2Cu_3O_{7-\delta}$ films were fabricated as thin as possible to achieve large $\Delta n/n$ ratios. The thinnest $YBa_2Cu_3O_{7-\delta}$ films found to be superconducting had an average thickness of ≈4-5 nm as determined from the extrapolated sputter rate. STM studies of similar films [21] revealed a thickness variation of ≈2-8 nm. Contamination of the interfaces was limited by performing all crucial steps of the sample preparation *in situ* in a specially designed vacuum system.

To rule out problems due to voltage pickup, all measurements were done in dc-mode. For each data point the drain source current I_{DS} was repeatedly reversed and the results were averaged.

3. Experiments

Through use of such samples, the transport properties of $YBa_2Cu_3O_{7-\delta}$ can be modified by the electric field in the normal as well as in the superconducting state as exemplified in Figures 2-4. Before these results are described in detail it has to be clarified whether these effects are field effects at all. As described in detail elsewhere [12], this is done by eliminating alternative explanations. By studying the effects as a function of gate and drain source current, for instance, it has been shown that they are not

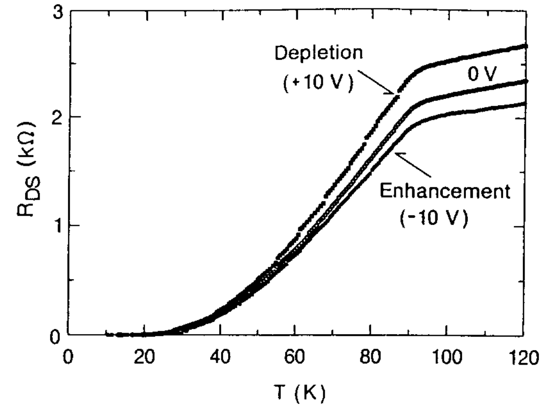

Fig. 2: Temperature dependence of the drain source resistance R_{DS} of an ≈7 nm thick $YBa_2Cu_3O_{7-\delta}$ film for three gate voltages applied: +10 V (solid squares), 0 V (open circles), and –10 V (solid circles). From [13].

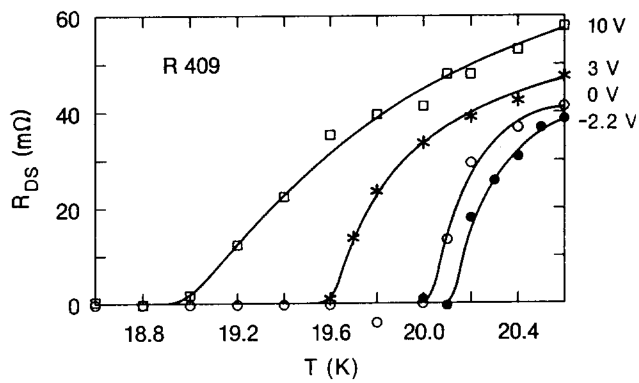

Fig. 3: Temperature dependence (close to T_{c0}) of the drain source resistance R_{DS} of an ≈10 nm thick $YBa_2Cu_3O_{7-\delta}$ film for four gate voltages: +10 V (depletion, open squares), +3 V (depletion, stars), 0 V (open circles), and –2.2 V (enhancement, solid circles). For this sample R_{DS}(300 K) ≈ 3600 Ω. From [13].

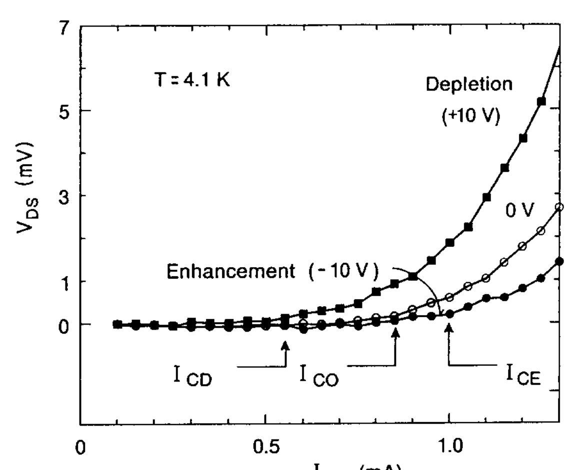

Fig. 4: Current dependence of the drain source voltage V_{DS} of the $YBa_2Cu_3O_{7-\delta}$ film shown in Fig. 2 for three applied gate voltages: +10 V (solid squares), 0 V (open circles), and –10 V (solid circles). From [18].

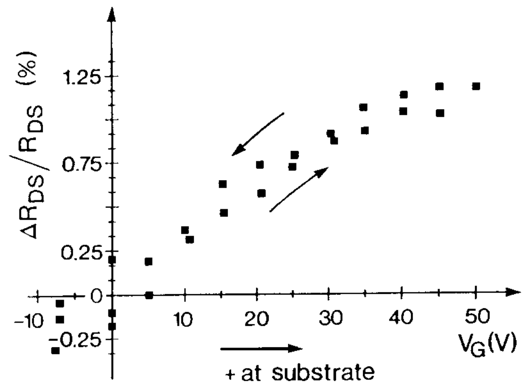

Fig. 5: Change of the drain source resistance R_{DS} caused by an applied gate voltage V_G of an ≈10 nm thick $YBa_2Cu_3O_{7-\delta}$ film. The change of resistance has been normalized to $R_{DS}(V_G = 0$ V). The data have been taken at 300 K. From [11].

caused by heating or by quasiparticle injection and that voltages induced in the drain source channel or in the contacts are irrelevant. Similarly, by fabricating samples of different structures [12] and by studying the response as a function of channel thickness it is concluded that electrostriction or piezoelectricity of the gate barrier play a minor role at most.

In general the data obtained agree with the most simple field effect prediction [6,12] as shall be demonstrated with the dependence of R_{DS} on the gate voltage V_G of an early sample which had an effect of $\Delta n/n \approx 10^{-2}$. As shown in Fig. 5 the $R_{DS}(V_G)$ dependence is approximately linear, ΔR_{DS} changes sign when the gate voltage is reversed and the polarity agrees with the one expected for depletion and enhancement of holes. It is pointed out that for n-type NdCeCuO films the opposite polarity has been reported [22], in agreement with depletion and enhancement of electrons. The measured value of $R_{DS}(V_G)$ corresponds to expectations: due to a gate capacitance of 2×10^{-7} F/cm^2, $V_G = 30$ V changes the electron density in the electrodes by 4×10^{13}/cm^2. Because the carrier density of $YBa_2Cu_3O_{7-\delta}$ is $3\text{-}5 \times 10^{21}$/cm^3, an areal density of mobile holes in the 10 nm thick channel layer of $3\text{-}5 \times 10^{15}$/cm^2 is derived. This means that within experimental error, a change of the free carrier density of ≈1% results in an equal change of R_{DS}, as expected for a standard field effect.

Thus it is summarized that the effects seen are generally consistent with a field-induced change of the superconductor carrier density close to the gate interface. It is important to realize that the electric field predominantly affects this interface layer which, at least for standard samples, is expected to have a higher defect density than the rest of the film. Therefore, by analyzing field effect experiments one has to take into account that they reflect properties of a superconductor rich in defects. These defects may exhibit an additional electrostatic life of their own and be susceptible to charging.

4. Field Effect Behavior

1) $T > T_c$

By applying the electric field the normal state resistance changes as described above. As demonstrated in Fig. 5, a linear $R_{DS}(V_G)$ characteristic is observed that sometimes shows a slight saturation behavior at higher fields [12], in agreement with observations by X.X. Xi et al. [23]. Hysteresis effects are present [12] which are attributed to the trapping of charges at the interface states. As a function of temperature, for $T > T_c$, the relative change of the drain source resistance $\Delta R_{DS}/R_{DS}$ is constant, which, in accordance with A.F. Fiory et al. [6], is interpreted as evidence for a temperature-independent carrier density.

2) $T \approx T_c$

Approaching T_c from above, the relative change of the drain source resistance $\Delta R_{DS}/R_{DS}$ diverges, indicating a field-induced shift of T_c. The T_c shift becomes evident if the behavior at T_{c0} is analyzed. As demonstrated by Fig. 3, gate voltages of the order of 10 V, can shift T_{c0} by more than 1 K [18]. It is pointed out that similar results have been obtained by X.X. Xi et al. using samples of another configuration prepared with different thin film techniques [13,23].

3) $T < T_c$

Below T_c, the current voltage characteristics $I_{DS}(V_{DS})$ of the drain source channel are modified by the electric field as shown in Fig. 4. The V_{DS} (I_{DS}) curve is well rounded and there is no marked kink that could serve as a definition of the critical current I_c. Smooth $I(V)$ curves are a characteristic of epitaxial films [24]; in these ultrathin samples the smoothness is even enhanced by the thickness variations of the $YBa_2Cu_3O_{7-\delta}$ films mentioned above. This implies that I_c has to be defined with some arbitrary criterion, which was chosen to be $R(100\ \text{K})/10^4 \approx 200$ mΩ.

As shown in Fig. 4, I_c depends sensitively on **E**, and can be shifted by a surprising 50% at 4.1 K. Because the sample in Fig. 4 had a T_c of ≈14 K, the shift of I_c is not regarded as a secondary effect resulting from a T_c shift. Remarkably, the magnetic field dependence of the critical current $I_c(B)$ of the sample shown in Fig. 4 is the same as that of conventional, 100 nm thick $YBa_2Cu_3O_{7-\delta}$ films which are known to be limited by depinning. This suggests that also for this ultrathin film, I_c is depinning-limited and that the electric field changes the strength of the pinning force, probably by altering the depths of the pinning potentials [16,18].

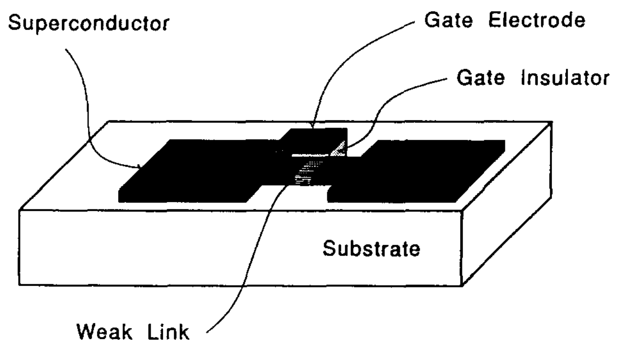

Fig. 6. Sketch of a sample where a superconducting weak link is controlled by an electric field. From [26].

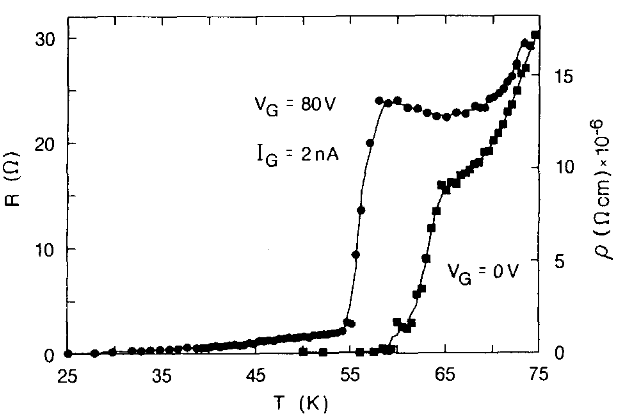

Fig. 7. $R_{DS}(T)$ curves of an $YBa_2Cu_3O_{7-\delta}$ film containing weak links for $I_{DS} = 200$ nA and gate voltages (a) $V_G = 0$ V, and (b) $V_G = 80$ V ($I_G = 2$ nA). From [26].

5. Electric Field Effects in $YBa_2Cu_3O_{7-\delta}$ Films Containing Weak Links

As described above, electrostatic screening counteracts the propagation of electric fields into the interior of the superconducting film and thus reduces the field effects. This suggests that an additional reduction in screening, attained for example by using samples into which weak links have been incorporated (Fig. 6), would help increase ι and thus result in even larger field effects. Besides their sensitivity to electric fields, such weak link structures may have another interesting feature. If the weak links are Josephson junctions, three terminal Josephson junctions (JOFETs) are obtained, and their gate voltage can be used for control, switching and trimming purposes. This is of interest for a wide range of applications.

As large-angle grain boundaries in $YBa_2Cu_3O_{7-x}$ films have been shown to act as Josephson junctions [25], one way to incorporate weak links is to add grain boundaries to the drain-source channel of standard field effect structures. Thus we have prepared numerous samples into which grain boundaries were inserted by using substrates with vicinal surfaces, by employing substrates with sharp edges or small grooves, or by fabricating bicrystalline drain-source channels.

In the following we focus on the behavior of samples for which submicron grooves were used to create the weak links.

The trenches in the substrate surface were produced by polishing the substrates with 1 μm diamond paste on a soft plastic foil, which yields a fine network of submicron grooves on the substrate surface. The groove density was of the order of 10^4/cm and the average depth and width of the trenches on top of the sputtered $SrTiO_3$ film were found by atomic force microscopy to be ≈300 Å and ≈500 Å, respectively. Since it is known that grooves and edges on substrate surfaces provoke grain boundaries in $YBa_2Cu_3O_{7-\delta}$ films, it is supposed in our case that the modified substrate surfaces give rise to grain boundary networks in the drain-source channels.

To demonstrate the large field effects obtainable, we present the behavior of one particular sample with large field effects. Further data can be found in Ref. 26.

Figure 7 shows the DS-resistance of this sample near T_{c0} as a function of temperature, measured with a DS-current of 200 nA for gate voltages of $V_G = 0$ V and $V_G = 80$ V (depletion). As shown, the transition temperature $T_{c0} \approx 60$ K is shifted by more than 10 K with $V_G = 80$ V and a gate current of $I_G = 2$ nA.

Samples of this type differ from conventional samples only with respect to the presence of weak links, yet they show a much greater shift of T_{c0}. The large field effects are therefore attributed to the weak links. Evidently, the shifts are induced in the weak links predominantly by the applied electric fields and not by I_G, first because they scale with V_G, second because large shifts have been obtained with small gate currents (≤1 nA), and third because T_c is increased in the enhancement mode (by 0.65 K for $V_G = 4.5$ V). As the polarity of the effects is consistent with the movement of holes in the weak links, in contrast to the polarity observed for moving oxygen ions [27], it is suggested that the effects are primarily based on the change of the hole density.

I_G increases exponentially with V_G. Thus for gate voltages V_G above 100 V, the value of I_G could be varied significantly while causing only slight electric field variations. As only a small change of V_G caused the $R(T)$ curves to shift noticeably in this parameter regime, it is concluded that these shifts are based in part on the higher gate currents involved. Since these currents were still small compared to the critical current, the enhancement effect is tentatively attributed to non-equilibrium effects caused by quasiparticle injection into the grain boundaries.

It is noted that the enhanced ι for samples containing weak links allows the achievement of consider-

Table I: Electromagnetic Fields and Superconductivity

Magnetic Fields	Electric Fields
$\lambda_m = \left(\frac{m^*}{\mu_0 n^* e^{*2}} \right)^{1/2}$	$\lambda_{el} = \left(\frac{\varepsilon_r^{sc} \varepsilon_0}{e^2 \frac{dN}{dE}(E_F)} \right)^{1/2}$
$\kappa = \frac{\lambda_m(T)}{\xi(T)}$ $< 1/\sqrt{2}$ Type I; $> 1/\sqrt{2}$ Type II	$\iota(T) = \frac{\lambda_{el}(T)}{\xi(T)}$ < 1 E effects are averaged out; > 1 ψ is sensitive to **E**
in bulk: $h/2e$	e
B affects $\vec{\nabla}\psi$	**E** affects $\lvert\psi\rvert$
Physics: magnetic flux structures and their interactions with the superconductor	Influence of n, E_F, Δ, U_{con} on any superconducting property
Devices: I and **B** controlled small signal devices (Squids, FFTs), power transmission, magnets...	Voltage controlled FETs, phonon generators, detectors...

able field effects with high-T_c thicker than standard drain source channels and thus have a higher T_c, which is of importance for potential applications.

6. Comparison of the Effects of Electric and Magnetic Fields on Superconductors

There is a remarkable analogy between the effects of electric and of magnetic fields on superconductivity which shall be elucidated in this chapter (see also Table 1).

First of all, by generating self-fields a superconductor shields its interior against electric or magnetic fields, generally damping them exponentially. For magnetic fields oriented in the z-direction, the corresponding shielding length is given by the Ginzburg-Landau penetration depth $\lambda_{ab}^{m}(T)$, for electric fields this is given by the much smaller electric penetration depth $\lambda_z^{el}(T)$.

The response of a superconductor to magnetic fields is characterized by the Ginzburg-Landau parameter $\kappa = \lambda_{ab}^{m}(T)/\xi_{ab}(T)$. For type I superconductors, $\kappa < 1/\sqrt{2}$ and the magnetic fields penetrate superconductors as flux tubes containing many vortices; for type II materials, $\kappa > 1/\sqrt{2}$ and the superconductor lets the field penetrate as single flux quanta.

The response of a superconductor to electric fields is classified in a similar way by the parameter $\iota(T) = \lambda_z^{el}/\xi_z(T)$. As described above, if $\iota < 1$, the electric field can influence the carrier density, but only in a region that is too small for the superconducting order parameter to respond to. Only if $\iota(T) > 1$ can the superconducting order parameter adapt to the modified carrier density and will depend sensitively on the applied field in this zone.

Next it is noted that both types of field may penetrate deeply into a superconductor, their sources being quantized in both cases. For magnetic fields, the quanta are flux lines with a charge of $h/2e$, for electric fields the quantum of the field source is the electronic charge e.

The analogy can be carried further by noting that the magnetic fields affect the *gradient* of the superconducting order parameter $\vec{\nabla}\Psi$ which is exploited in phase-sensitive devices like Squids, whereas electric fields change the order parameter's *magnitude* $|\Psi|$. Therefore electric fields are interesting for devices that exploit the value of the superconducting gap [28].

7. Summary

Owing to their low carrier densities, their high dielectric constants and their small coherence lengths the high-T_c cuprates are destined to change their transport properties with applied electric fields. In various experiments, field effects have been reported that agree in general with a model in which the electric field acts on the superconductor by changing its density of mobile carriers via band bending. Field effects have been reported for the normal state as well as for the superconducting phase. Concerning the latter it has been found that in epitaxial $YBa_2Cu_3O_{7-\delta}$ films the critical temperature of ultrathin films can be shifted by 1 K and that their pinning energy and hence their critical current can be varied up to 50% by gate voltages of the order of 10 V. In the case that weak links are incorporated into the high-T_c films, T_{c0} shifts can be enhanced to 10 K or more.

It is hoped that applied electric fields will be a key to basic studies of the influence of the carrier concentration on such fundamental properties of high-T_c superconductors as $T_c(n)$, $\lambda(n)$, and $\xi(n)$, and may provide new access to the macroscopic quantum state of superconductivity.

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