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Original contributions

Electric field effect on superconducting $YBa_2Cu_3O_{7-\delta}$ films

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Experimental evidence for a significant electric field effect in thin superconducting films of $YBa_2Cu_3O_{7-\delta}$ is presented. MISFET-type structures have been developed which allow the application of electric fields larger than 4×10^6 V/cm across insulating $SrTiO_3$ barriers into thin epitaxial $YBa_2Cu_3O_{7-\delta}$ channel layers. The results demonstrate that with these structures the electrical resistivity above T_c ($R=0$) and the density of free carriers in the $YBa_2Cu_3O_{7-\delta}$ films can be modified by 1-2% with gate voltages smaller than 50 V.

Introduction

In this paper we provide the first experimental evidence for a substantial effect of applied electric fields on the electrical conductivity of high-T_c superconductors. The occurrence of a significant electric field effect in high-T_c superconductors is important for two reasons:

1. The possibility of modifying the carrier concentration in a given sample, in a reversible and well-controlled manner without affecting the stoichiometry of the sample, opens a route to new experiments concerning the basic mechanism of superconductivity in copper oxides.
2. If the electric field effect is strong enough, it may provide the basis for applications of high-T_c superconductors as three terminal devices.

Shortly after the discovery of high-T_c superconductivity, Chaudhari et al. predicted [1] on simple theoretical grounds that high-T_c superconductors may exhibit an electric field effect to a much greater extent than low-T_c superconductors do. The length scale by which conducting materials screen electrostatic fields is given by the sum of the Debye length $L_D=(\varepsilon_0\varepsilon_r kT/q^2n)^{1/2}$ and the width of any depletion zones $L_{DZ}=N/n$. Here, ε_0 and ε_r are the dielectric constants of vacuum and of the material, respectively, q is the elementary charge, n the density of mobile carriers and N the areal density of induced charge carriers. Owing to their high carrier density, low-T_c superconductors usually screen electric fields so well that the fields have only a minor influence on materials properties [2]. To attenuate the screening, recent experiments on the electric field effect in low-T_c superconductors have focussed on systems with an exceptionally low carrier density. For example, field effects were studied by inducing superconductivity in semiconductors utilizing the proximity effect [3], or by using superconductors with an exceptionally low carrier density such as doped $SrTiO_3$ [4].

In high-T_c compounds larger field effects are expected owing to their intrinsically low carrier concentration and their small coherence length. The low carrier concentrations of about 3–$5\times10^{21}/cm^3$ [5] lead to screening lengths in the angstrom range, and the small coherence lengths allow the fabrication of ultrathin layers with respectable critical temperatures. Superconducting films as thin as 10–20 Å have already been grown [6]; such films may be penetrated to a considerable extent by electric fields. Due to these expectations, numerous studies on the electric field effect in copper oxide compounds have been performed [7–9], but only minor field effects in high-T_c superconductors have been reported. By applying electric fields across insulating kapton foils glued onto superconducting $YBa_2Cu_3O_{7-\delta}$ films, Fiory et al. [8] observed fractional shifts in the normal state resistivity of the $YBa_2Cu_3O_{7-\delta}$ films in the range of 10^{-5}. Using conventional $SrTiO_3$ substrates as gate insulators, Levy et al. [9] observed resistivity changes in semiconducting $YBa_2Cu_3O_6$ films, but did not report an effect for superconducting films.

Sample preparation

To be able to apply large electric fields to thin films of superconducting $YBa_2Cu_3O_{7-\delta}$, an inverted MISFET structure (Fig. 1) was used. In this structure, the superconducting film of thickness s is separated from a gate electrode by an insulating layer of thickness t. Such a

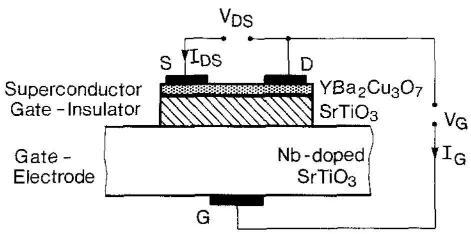

Fig. 1. Sketch of the inverted MISFET structure (cross section)

configuration allows considerable positive (negative) voltages V_G to be applied between the gate electrode and the superconductor in order to decrease (enhance) the density of mobile holes in the *p*-type superconducting channel.

Aside from the thickness of the superconductor, the resistivity ρ_G and the breakthrough strength E_{BD} of the insulator proved to be crucial parameters. The required values for E_{BD} and ρ_G can be simply estimated if space charge effects are neglected. To induce a surface charge density in the superconducting film which corresponds to the unperturbed density *n* of mobile carriers, the capacitor consisting of the gate electrode and the superconductor has to be biased with a voltage

$$V_G = qnst/\varepsilon_0\varepsilon_i, \qquad (1)$$

where ε_i is the dielectric constant of the insulator. Equation (1) implies that to modulate the carrier density in high-T_c superconductors substantially, the product $\varepsilon_i \times E_{BD}$ of the dielectric constant and the breakdown field has to be of the order of 10^8 V/cm. (For comparison, SiO_2 has an $\varepsilon_i \times E_{BD}$ product of 4×10^7 V/cm at room temperature [10]).

In addition, the normal state resistivity of the insulator has to be sufficiently high to avoid leakage currents which could interfere with the measurement. Quantitatively, the leakage current I_G at the required gate voltage has to be negligible compared to the bias current I_{DS} used for the resistivity measurement of the superconducting film. For a typical case of $I_{DS} = 10$ µA and an area of the gate electrode of 10 mm^2, the resistivity has to be greater than 10^{14} Ωcm/ε_i at operating temperature to obtain $I_G < I_{DS}/100$.

These requirements indicate that it may be advantageous to utilize insulating layers with high dielectric constants. For this reason and for its compatibility with the growth of $YBa_2Cu_3O_7$, $SrTiO_3$ was selected in the present paper as barrier material. MISFET structures with $SrTiO_3$ barrier layers were fabricated in two different ways:

1. In the first configuration (see Fig. 1), which was the one used for most of the measurements because it allowed the application of larger electric fields, the gate electrode consisted of an *n*-type {100}-oriented 0.05% Nb-doped $SrTiO_3$ single crystal grown by the zone melting technique. On top of the substrates, {100}-oriented insulating layers of $SrTiO_3$ were epitaxially grown by reactive rf-magnetron sputtering at 0.05 Torr in an O_2/Ar atmosphere at 650 °C (temperature of the sample holder). Without breaking vacuum, superconducting $YBa_2Cu_3O_{7-\delta}$ films were grown epitaxially on top of the insulating $SrTiO_3$ layers by hollow cathode magnetron sputtering [11]. Contacts were made to the $YBa_2Cu_3O_{7-\delta}$ top layer by sputtered Au pads and to the conducting substrate by diffusing silver into the Nb-doped $SrTiO_3$.

2. Reference samples were prepared using {100}-oriented $SrTiO_3$ substrates as insulators that had been polished to a thickness of 20–30 µm. $YBa_2Cu_3O_{7-\delta}$ films were sputtered on top of the thinned substrates. Gold pads on the back of the substrates served as gate contacts.

Measurement techniques

To avoid problems with voltage pickup, all measurements were performed in *dc* mode. The resistivity of the $YBa_2Cu_3O_{7-\delta}$ films was measured by a current-controlled, four-point measurement. For each data point, the polarity of the current source was reversed and the results averaged. The current voltage characteristic of the insulating layers was measured by a two-point or a four-point technique; no difference between the results obtained with the two methods was found.

Results

A typical characteristic for a type 1 sample of the current I_G through the insulator as a function of applied gate voltage V_G is shown in Fig. 2. The characteristic is the

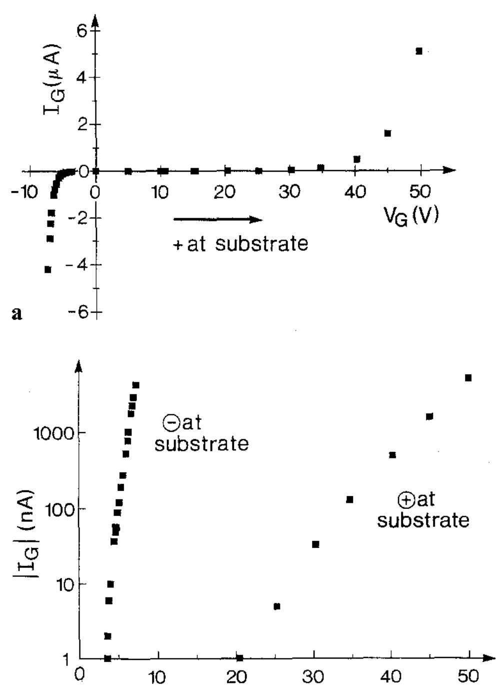

Fig. 2. a Gate current I_G as a function of gate voltage V_G for a MISFET structure with a gate area of 10 mm^2 at 300 K. **b** Same as **a** on a logarithmic current scale

one expected for a *pin*-junction, the superconductor and the substrate being the *p* and *n* electrodes, respectively. The insulating barriers have resistivities of up to $1\times10^{13}\,\Omega$cm at a forward bias of 3 V and up to $1\times10^{14}\,\Omega$cm at a reverse bias of 20 V. Breakdown fields at room temperature of 2×10^{5} V/cm and 4×10^{6} V/cm were obtained in the forward and reversed directions, respectively. The capacitance of this sample is 2×10^{-7} F/cm^2 at room temperature. This value corresponds to a relatively low $\varepsilon_i=36$ ($s=100$ Å, $t=1600$ Å). This low dielectric constant may be caused by insulating surface layers observed on the Nb-doped $SrTiO_3$ substrates, in agreement with a report by Hasegawa et al. [12]. These layers had breakdown voltages of about 2 V. Nevertheless, the $\varepsilon_i E_{BD}$ products of the $SrTiO_3$ barrier layers under reverse bias lie at 10^8 V/cm, which is the lower limit required by (1).

The influence of the gate voltage V_G on the channel resistance R_{DS} of the same sample is shown in Fig. 3a. The sample is characteristic of all type 1 samples we have fabricated and analyzed. The temperature dependence of the resistance $R_{DS}(T)$ of the $YBa_2Cu_3O_{7-\delta}$ film is shown in Fig. 3b. Figure 3a clearly shows that the dependence of the measured normal state resistivity on gate voltage is approximately linear, that the effect changes sign when the gate voltage is reversed, and that changes in resistivity of more than 1% are obtained for electric fields above 2×10^{6} V/cm.

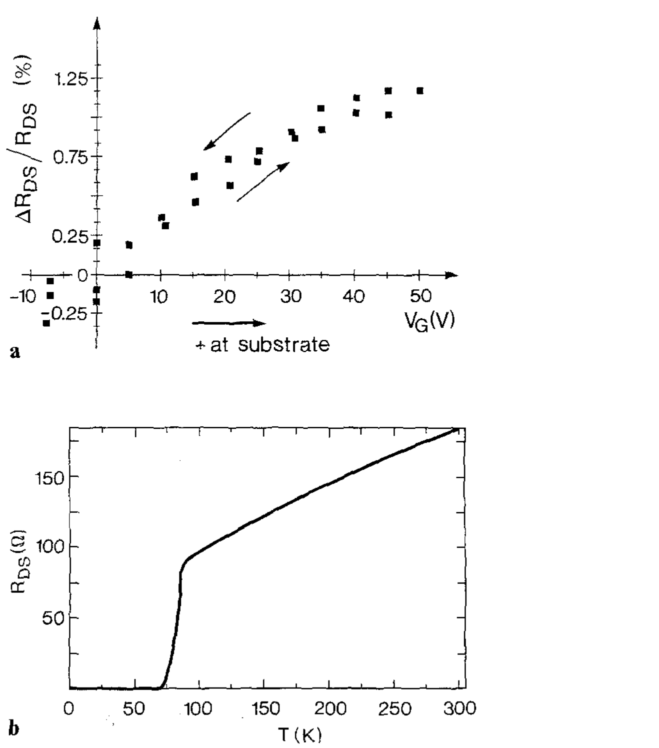

Fig. 3. **a** Change of the resistance R_{DS} caused by an applied gate voltage V_G for the sample shown in Fig. 2. The change of resistance has been normalized to $R_{SD}(V_G=0)$. The data have been taken at 300 K with a channel current $I_{DS}=1$ mA. **b** $R_{DS}(T)$ of the same sample

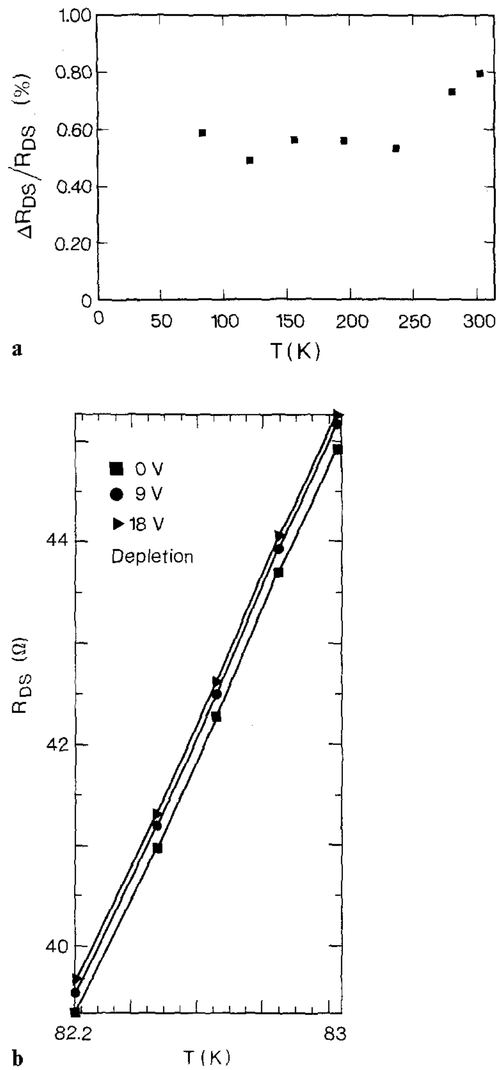

Fig. 4. **a** Change of the resistance R_{DS} as a function of temperature for the sample shown in Fig. 2 cause by a gate voltage $V_G=20$ V (depletion). The resistance change R_{DS} has been normalized to $R_{DS}(V_G=0, T)$. **b** $R_{DS}(T)$ of the same sample near T_c (midpoint) for a few gate voltages V_G

The temperature dependence of the voltage-induced relative change of the channel resistance $\Delta R_{DS}/R_{DS}(V_G, T)$ is shown for the same sample in Fig. 4. As shown by this figure, within experimental scatter, the fractional change of the channel resistance $\Delta R_{DS}/R_{DS}$ as a function of temperature is constant. A temperature-independent $\Delta R_{DS}/R_{DS}(V_G)$ ratio is observed down to $T_c(R_{DS}=0)$. The changes of the channel resistance at midpoint T_c are shown in Fig. 4b. The gate voltage-induced change of the channel resistance corresponds to a change of the $R_{DS}(T)$ characteristic at midpoint T_c of 50 mK for $V_G=18$ V. We point out that the thin $YBa_2Cu_3O_{7-\delta}$ film of this sample had a broad resistive transition ($\simeq 12$ K from 10% to 90% of $R_{DS}(100\text{ K})$), which leads to a large shift at T_c for a given resistance change.

Before analyzing these characteristics in more detail, the question shall be addressed whether the effect shown in Fig. 3a is indeed the expected electric field effect or is caused by some other mechanism.

To answer this question the following set of experiments was performed:

1. Measurements of $R_{DS}(V_G)$ were made on type 1 samples in which the resistances of the barrier layers were lower by a factor of 500 (at 20 V) than the sample shown in Fig. 3a. They showed the same $R_{DS}(V_G)$ characteristic, demonstrating that the observed effect is not caused by the finite gate current I_G. In addition, heating effects would not be expected to result in a linear $R_{DS}(V_G)$ characteristic, but rather to one proportional to $I_G \times V_G$. Furthermore, it is apparently not possible to explain the observed enhancement of conductivity at forward bias (Fig. 3a) by heating.
2. The elucidate whether V_G primarily affects the channel resistance R_{DS} or whether the effect is based on a change of V_{DS}, R_{DS} was measured for different channel currents I_{DS}. As shown in Fig. 5, the induced change of R_{DS} does not depend on I_{DS}, even if I_{DS} is varied by four orders of magnitude. This proves that an applied gate voltage results in a change of the channel resistance R_{DS} and does not induce significant voltages in the channel layer.
3. It is conceivable that the observed change of the channel resistance R_{DS} is caused by mechanical stress which results from electrostrictive or possible piezoelectric effects [13] in the $SrTiO_3$ barrier layer. The linearity of the $R_{DS}(V_G)$ characteristic rules out electrostrictive effects which are expected to be proportional to V_G^2. Possible piezoelectric effects, proportional to V_G, have to be considered in more detail, although it seems unlikely that they could result in a fractional resistance change that is temperature-independent.

A strong indication that a mechanical stress effect is not the primary cause of the observed modulation of the channel resistance is the very similar behavior of type 1 and type 2 samples within the field range ($< 3 \times 10^5$ V/cm) accessible with type 2 samples, even though their mechanical configuration differs substantially. To further clarify this issue, four-layer heterostructures were prepared as shown in Fig. 6. Such samples allow one to detect mechanical effects in the following way: if mechanical effects are present, any voltage applied between the substrate and the bottom superconducting layer would induce mechanical tension (stress) in both the bottom and the top superconducting layer, since both are attached to the same (thick) substrate. In that case, the channel resistance R_{DS}^{top} of the top superconducting film should depend on the voltage V_G between the substrate and the lower superconducting layer. Experimentally, no change of R_{DS}^{top} with V_G was detected. It is concluded that neither electrostrictive nor piezoelectric effects contribute significantly to the observed field effect.

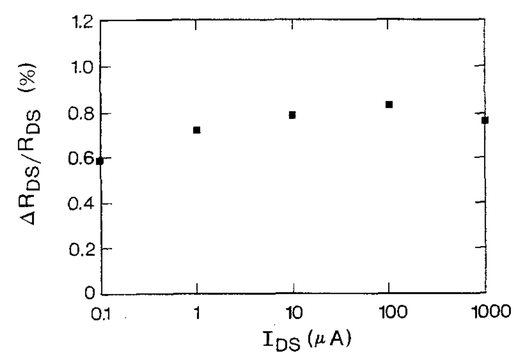

Fig. 5. Change of the resistance R_{DS} of the sample shown in Fig. 2 caused by a gate voltage $V_G = 20$ V (depletion) as a function of the channel current I_{DS}

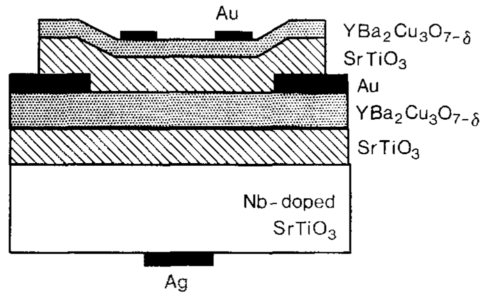

Fig. 6. Sketch of the four-layer heterostructure (cross section)

Discussion

In the following it shall be shown that all of the experimental results presented above can indeed be understood in terms of an electric field effect which controls the concentration of mobile charge carriers in the channel layers.

First we point out that the measured polarity of the voltage-induced resistance change agrees with theoretical expectations. A positive voltage V_G at the gate electrode depletes the concentration of mobile holes in the channel and therefore increases the channel resistance R_{DS}.

Second, the measured $R_{DS}(V_G)$ value agrees well with that expected for an electric field effect: applying 30 V to the sample shown in Fig. 3a, which has a capacitance of 2×10^{-7} F/cm^2, induces a change in the electron density on the electrodes of 4×10^{13}/cm^2. On the other hand, $YBa_2Cu_3O_7$ has a carrier density of about 3-5$\times 10^{21}$/cm^3 [5], which corresponds to an areal density of mobile holes in the 100 Å thick channel layer of 3–5$\times 10^{15}$/cm^2. This means that within experimental error, a change of the free carrier density in the channel of up to 1% at any temperature results in an equal change in R_{DS}. Consequently, all effects observed can be ascribed to changes of the normal state resistivity, even at T_c. This implies that in the samples studied, a change of the carrier density of 1–2% does not change the condensation temperature noticeably.

Finally, it is mentioned that pronounced hysteresis and relaxation effects with a time scale of seconds have been observed in all samples (type 1 and 2). Such hysteresis is seen in Fig. 3a. These effects have not yet been analyzed in detail, but have been found to be consistent with the trapping of charges at sites close to the $YBa_2Cu_3O_{7-\delta}/SrTiO_3$ interface.

Summary and conclusions

MISFET-type heterostructures consisting of $YBa_2Cu_3O_{7-\delta}/SrTiO_3$ multilayers have been developed which allow the application of electric fields larger than 4×10^6 V/cm to thin, superconducting films of $YBa_2Cu_3O_{7-\delta}$. Utilizing these devices, substantial electric field effects have been found: changes in the channel resistance of more than 1% were observed in 100 Å thick $YBa_2Cu_3O_{7-\delta}$ films at a gate bias of 30 V. These effects are three orders of magnitude larger than the highest values previously reported. Further, the observed resistivity changes are attributed to equally strong changes of the carrier density in the high-T_c superconductor. We point out that by optimizing the sample configuration the technology presented may readily allow the carrier density in superconducting channels to be controlled to an even greater extent.

The observed field effect opens the way to basic studies of the influence of the carrier concentration on fundamental properties of high-T_c superconductors and may also lead to three terminal device-type applications of high-T_c superconductors.

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