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# ELECTRIC FIELD EFFECT ON SUPERCONDUCTING $YBa_2Cu_3O_{7-\delta}$ FILMS

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MISFET-type structures have been developed that allow the application of electric fields larger than $4 \times 10^6$ V/cm into 100 Å thick, superconducting $YBa_2Cu_3O_{7-\delta}$ channel layers. With these structures, the carrier density and the electrical resistivity of $YBa_2Cu_3O_{7-\delta}$ can be modified in the percent range by gate voltages of 50 V.

## 1. INTRODUCTION

Shortly after the discovery of high-$T_c$ superconductivity, these materials were predicted to exhibit an electric field effect much stronger than conventional low-$T_c$ superconductors.[1] This expectation and subsequent suggestions for applications are based on the idea that the length scale by which external electrostatic fields are shielded in the depletion mode is the Debye length $L_D \propto n^{-1/2}$, where $n$ is the density of mobile carriers. In high-$T_c$ cuprates, where $n \simeq 3\text{-}5 \times 10^{21}/\text{cm}^3$, screening lengths of a few Å are expected. Furthermore, the short coherence length of high-$T_c$ cuprates, allows the fabrication of ultrathin layers, which may be substantially penetrated by electric fields. Encouraged by such considerations, numerous studies on the electric field effect in high-$T_c$ compounds have been performed.[2,3]

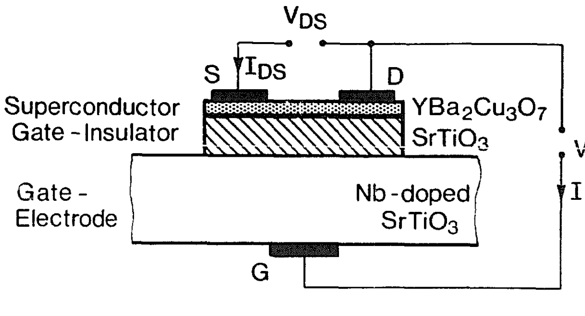


FIGURE 1. Sketch of the inverted MISFET-structure (cross section).

Here, field effect studies are reported that take advantage of epitaxially grown $SrTiO_3$ films incorporated into an inverted MISFET-type structure as shown in Fig. 1. A superconducting $YBa_2Cu_3O_{7-\delta}$ film of thickness $s$ is separated from a gate electrode by the insulating $SrTiO_3$ layer of thickness $t$. Such a configuration allows considerable positive (negative) voltages $V_G$ to be applied between the gate electrode and the superconductor in order to decrease (enhance) its density of mobile holes.

## 2. SAMPLE PREPARATION

In most of the heterostructures investigated, the gate electrode consists of an $n$-type (100) oriented 0.05% Nb-doped $SrTiO_3$ single crystal grown by the zone melting technique. On top of this crystal, (100)-oriented $SrTiO_3$ is grown by rf-magnetron sputtering at 0.05 Torr in an $Ar/O_2$ atmosphere. Without breaking vacuum, $YBa_2Cu_3O_{7-\delta}$ films were grown epitaxially on top of the $SrTiO_3$ layers by hollow cathode magnetron sputtering. Contacts were provided by Au pads.[3]

## 3. RESULTS

The insulating barriers have resistivities of up to $1 \times 10^{13}$ Ωcm at a forward bias of 3 V, and up to $1 \times 10^{14}$ Ωcm at a reverse bias of 20 V, allowing the channel layer resistance $R_{DS}$ to be measured without interference by excessive gate leakage current.

Breakdown fields $E_{BD}$ of $2 \times 10^5$ V/cm and $4 \times 10^6$ V/cm were obtained at 300 K in the forward and reverse direction, respectively. At lower temperature, $E_{BD}$ decreases, indicating avalanche breakdown. Barrier capacitances of $2 \times 10^{-7}$ F/cm$^{-2}$ are obtained at 300 K, corresponding to a dielectric constant $\varepsilon_r$ of 40. Resistivity data are obtained by a current-biased four-point measurement in dc-mode. For each data point the polarity of the current source was reversed and the results averaged.

The effect of the gate voltage on the drain-source resistance at room temperature is shown in Fig. 2 for a sample with $s \simeq 100$ Å, $t \simeq 1600$ Å and $T_c$ $(R = 0) \simeq 70$ K. The figure – characteristic for all samples investigated – shows that the normal-state resistivity of the $YBa_2Cu_3O_{7-\delta}$ film depends linearly on gate voltage, that the sign of $\Delta R_{DS}$ depends on the polarity of $V_G$, and that changes in resistivity of more than 1% are obtained for electric fields above $2 \times 10^6$ V/cm. Hysteresis effects as shown in Fig. 2 have been found to be consistent with trapping of charges close to the $YBa_2Cu_3O_{7-\delta}/SrTiO_3$ interface. The relative change $\Delta R_{DS}/R_{DS}$ is constant as a function of temperature for the samples investigated, leading to a shift of $R_{DS}(T)$ at midpoint $T_c$ ($\simeq 82.5$ K) of $\simeq 50$ mK for $V_G = 18$ V. Further characteristics have been described elsewhere.[3]

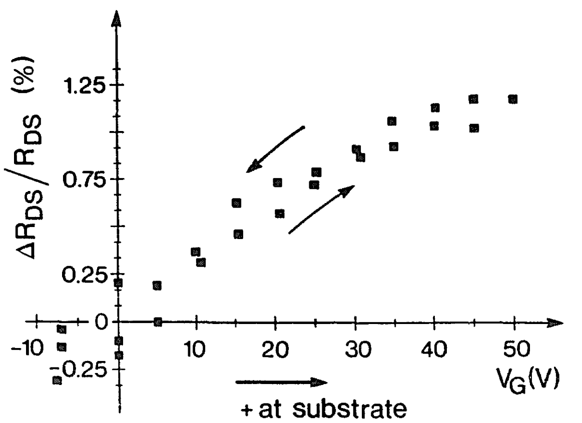


FIGURE 2. Change of the normal state resistance of the $YBa_2Cu_3O_{7-\delta}$ layer caused by the electric field of an applied gate voltage $V_G$ at 300 K.

## 4. DISCUSSION

The measured $R_{DS}(V_G)$ agrees well with expectations: Applying 30 V to the sample shown in Fig. 2 with a capacitance of $\simeq 2 \times 10^{-7}$ F/cm$^2$ induces a change in the electron density in the channel layer of $\simeq 4 \times 10^{13}$/cm$^2$. On the other hand, $YBa_2Cu_3O_{7-\delta}$ has a carrier density of $\simeq$ 3-5 $\times 10^{21}$/cm$^3$, which corresponds to a density of mobile holes in the channel layer of 3-5 $\times 10^{15}$/cm$^2$. Therefore, within experimental error, a change in the carrier density of $\simeq$ 1% results in an equal change of $R_{DS}$.

It is pointed out that the observed field effect greatly exceeds the values reported previously for superconducting high-$T_c$ cuprates. Optimizing the sample configuration may allow us the control of the carrier concentration in superconducting channels to an even greater extent. The occurrence of a significant electric-field effect in high-$T_c$ superconductors may open a route to new experiments concerning fundamental properties of high-$T_c$ compounds, for example, by changing the carrier concentration in a given sample in a well-controlled manner without affecting its stoichiometry. Also, a sufficiently strong electric-field effect may provide a basis for future applications of high-$T_c$ superconductors.

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