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Electric Field Effects in $YBa_2Cu_3O_{7-\delta}$ Films

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A brief summary of the electric field effects on the normal and the superconducting state of high-T_c superconductors is given. Experiments are presented in which electric fields were used to modulate the transport properties of weakly linked $YBa_2Cu_3O_{7-\delta}$ films. It is found that the critical temperature T_{c0} of such films can be reduced by ≈ 10 K by applying electric fields of ≈ 6 MV/cm. In one case, T_{c0} shifts of up to 25-30 K were observed. These are by far the largest T_c shifts reported for any superconducting system.

1. INTRODUCTION

Since the beginning of the 1960s there has been an ongoing effort to use electric fields to control the transport properties of superconducting films. These activities were extended both experimentally and theoretically to the high-T_c cuprates shortly after the discovery of these materials because they are exceptionally well suited for field effect studies [1]. 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 substantially.

In this contribution field effect experiments performed with $YBa_2Cu_3O_{7-\delta}$ films at the IBM Zurich Research Laboratory will be discussed.

2. SAMPLE PREPARATION AND MEASUREMENT TECHNIQUE

The standard sample configuration used in the experiments is shown in Fig. 1. An n-type {100}-oriented 0.05% Nb-doped $SrTiO_3$ single crystal is used as the substrate and gate electrode. Its surface conductivity is enhanced by means of an $\approx$4-nm-thin Pt film grown by 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). Subsequently, $YBa_2Cu_3O_{7-\delta}$ films were sputtered 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 $SrTiO_3$. Lastly, some of the samples were sealed with an insulating layer of $YBa_2Cu_3O_{6+x}$ laser-deposited at room temperature. To avoid leakage through pinholes, relatively thick (≈ 150 nm) insulating $SrTiO_3$ layers were employed, whereas the $YBa_2Cu_3O_{7-\delta}$ films were fabricated as thin as possible to achieve large $\Delta n/n$ ratios. Contamination of the interfaces was limited by performing all crucial steps of the sample preparation *in situ*.

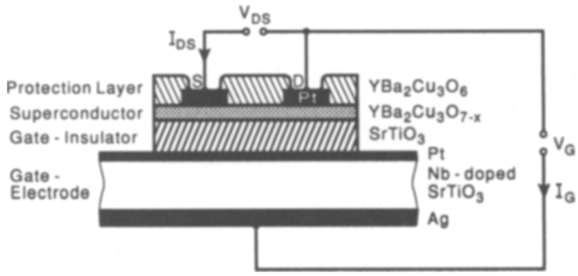

Figure 1. Sample configuration used for the study of field effects.

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.

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3. EXPERIMENTS

By using 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. By applying electric fields of a few MV/cm, the normal state resistance can be changed by $\approx 30\%$ [1], the critical temperature T_{c0} by $\approx$ 2-3 K [1,2] and the critical current density at 4.2 K by about 50% [2].

Electrostatic screening counteracts the propagation of electric fields into the interior of the superconducting film and thus reduces the field effects. Therefore, an additional reduction in screening, achieved for example by using samples into which weak links have been incorporated (Fig. 2), would 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.

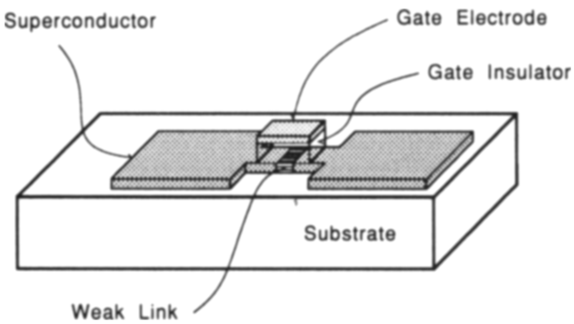

Figure 2. Sketch of a sample where a superconducting weak link is controlled by an electric field. From [3].

In the following we focus on the behavior of samples for which grooves with a width and a depth of a few 10 nm were used to create the weak links [3]. 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.

Figure 3 shows the drain-source resistance of such a sample with a thickness of the $YBa_2Cu_3O_{7-\delta}$ drain-source channel of ≈ 12 nm near T_{c0} as a function of temperature, measured with a drain-source 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. Moreover, in another sample that had a nominal film thickness of only ≈ 8 nm, the critical temperature could be reduced from ≈ 30 K to below 4.2 K by applying the field [3].

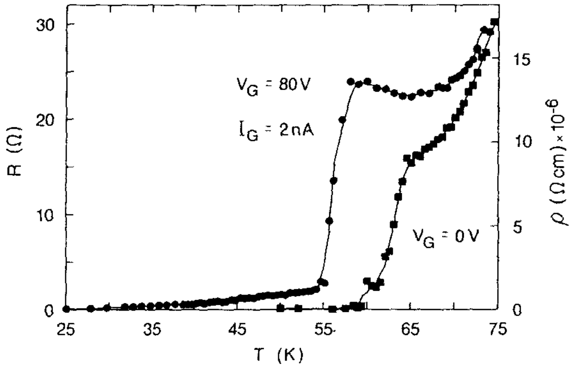

Figure 3. $R_{DS}(T)$ curves of an $YBa_2Cu_3O_{7-\delta}$ film containing weak links for $I_{DS} = 200$ nA and gate voltages (a) $V_G = 0$ V, and (b) $V_G = 80$ V ($I_G = 2$ nA). From [3].

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 electric fields applied and not by I_G, first because they scale with V_G, second because large shifts have been obtained with small gate currents ($\lesssim 1$ 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, contrary to the polarity observed for moving oxygen ions, it is suggested that the effects are primarily based on the change of the hole density.

It is noted that the enhanced electric field sensitivity of samples containing weak links allows considerable field effects to be achieved with high-T_c films that have relatively thick drain-source channels and thus have a high T_c, which is of importance for potential applications.

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