Influence of Electric Fields on Pinning in $YBa_2Cu_3O_{7-\delta}$ Films

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Experimental evidence is provided that the pinning force and the critical current density of $YBa_2Cu_3O_{7-\delta}$ films can be controlled by electric fields. This novel effect is attributed to field-induced changes of the density of mobile charge carriers in the superconductor.

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For more than thirty years, there have been efforts to change the carrier concentration in superconductors by applying electric fields [1]. Relatively large effects are expected for superconductors with a low concentration of mobile charge carriers n, because of larger screening lengths. High-T_c superconductors such as $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_8$ have an intrinsic carrier concentration $n \simeq (2\text{–}5)\times 10^{21}/\text{cm}^3$, which is relatively small, and therefore have provoked the search for an electric-field effect in these compounds [2,3].

For the temperature range above the critical temperature, $T \gtrsim T_c$, substantial effects have recently been reported for $YBa_2Cu_3O_{7-\delta}$ [4]. In this Letter we provide direct evidence of a strong electric-field effect below T_c. It will be shown that with fields of $\simeq 2\times 10^5$ V/cm generated by voltages of $\simeq 10$ V the critical current density of $YBa_2Cu_3O_{7-\delta}$ films can be modified by $\simeq 50\%$. This effect is attributed to an equal change of the global pinning force of magnetic-flux lines caused by the change of the density of mobile charge carriers with the applied electric field.

To apply electric fields to thin $YBa_2Cu_3O_{7-\delta}$ layers, inverted metal-insulator-semiconductor field-effect-transistor- (MISFET-) type heterostructures were fabricated. As shown in Fig. 1, the surfaces of 0.05%-Nb-doped single crystals of $SrTiO_3$ grown by the zone-melting technique were passivated with an epitaxial Pt layer, grown to a thickness of $\simeq$20–50 Å by electron-beam evaporation. Subsequently, (100)-oriented, $\simeq$500-nm-thick, insulating $SrTiO_3$ layers and 4–10-nm-thick $YBa_2Cu_3O_{7-\delta}$ layers were sputter deposited. Patterning of the $YBa_2Cu_3O_{7-\delta}$ films was avoided in order not to degrade their superconducting properties. Four Au contact pads each measuring 1×1 mm^2 were evaporated in an approximately square arrangement, the side length of the squares being about 3 mm. These pads were used to make four-point electrical transport measurements. A fifth contact was used to supply the gate voltage to the $YBa_2Cu_3O_{7-\delta}$ film. Contacts to the gate electrode were provided by diffusing silver into the backside of the $SrTiO_3$(Nb) substrates. Further details of the sample preparation may be found in Refs. [4] and [5]. Samples prepared in this manner had a gate resistivity of 10^{11}–10^{12} Ω cm at 10 V in both polarities, increasing exponentially with decreasing gate voltage.

Since the effect was observed to become smaller with increasing thickness s of the superconducting layer, we focus in the following on the sample with the smallest thickness s which was still superconducting. As determined by extrapolating sputter rates measured for thicker

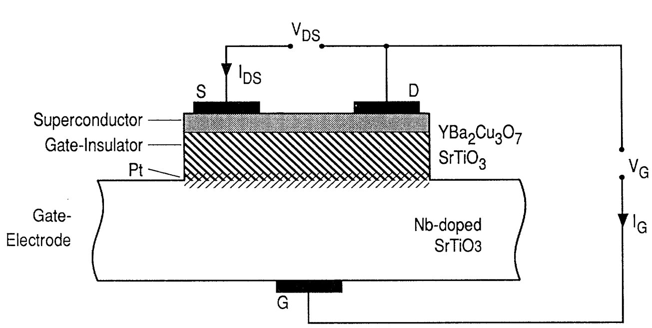

FIG. 1. Sketch of the inverted MISFET structure (cross section).

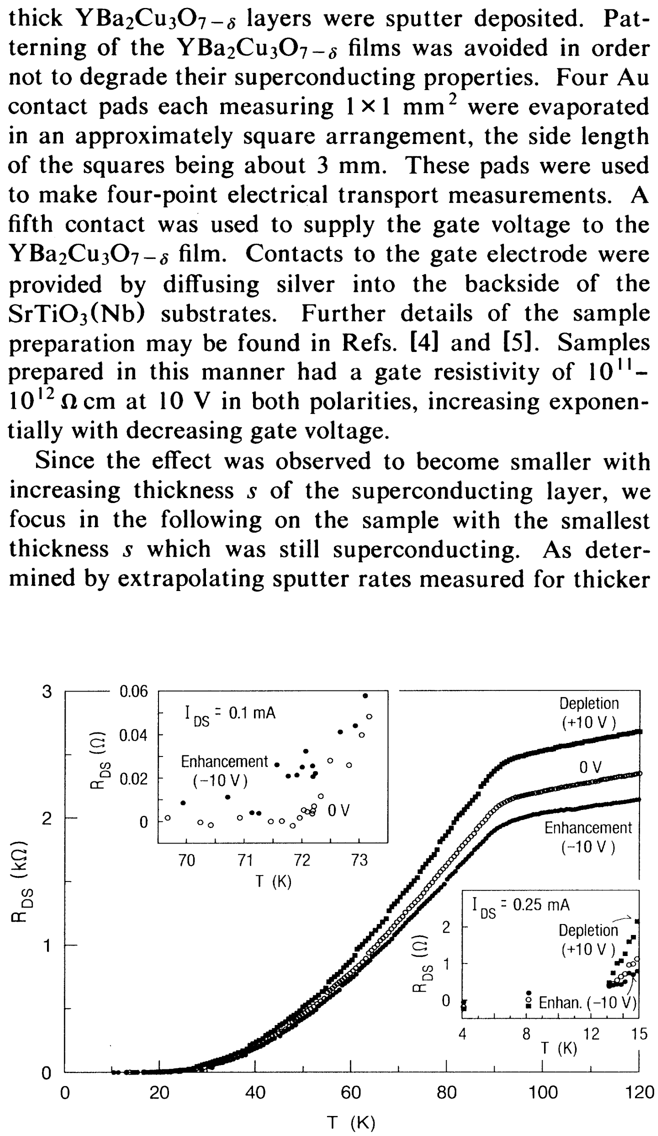

FIG. 2. Temperature dependence of the drain-source resistance (R_{DS}) for three applied gate voltages: +10 V (solid squares), 0 V (open circles), and −10 V (solid circles). The behavior of R_{DS} in the vicinity of T_{c0} is shown in the insets for this same sample (lower right) and a different sample (upper left).

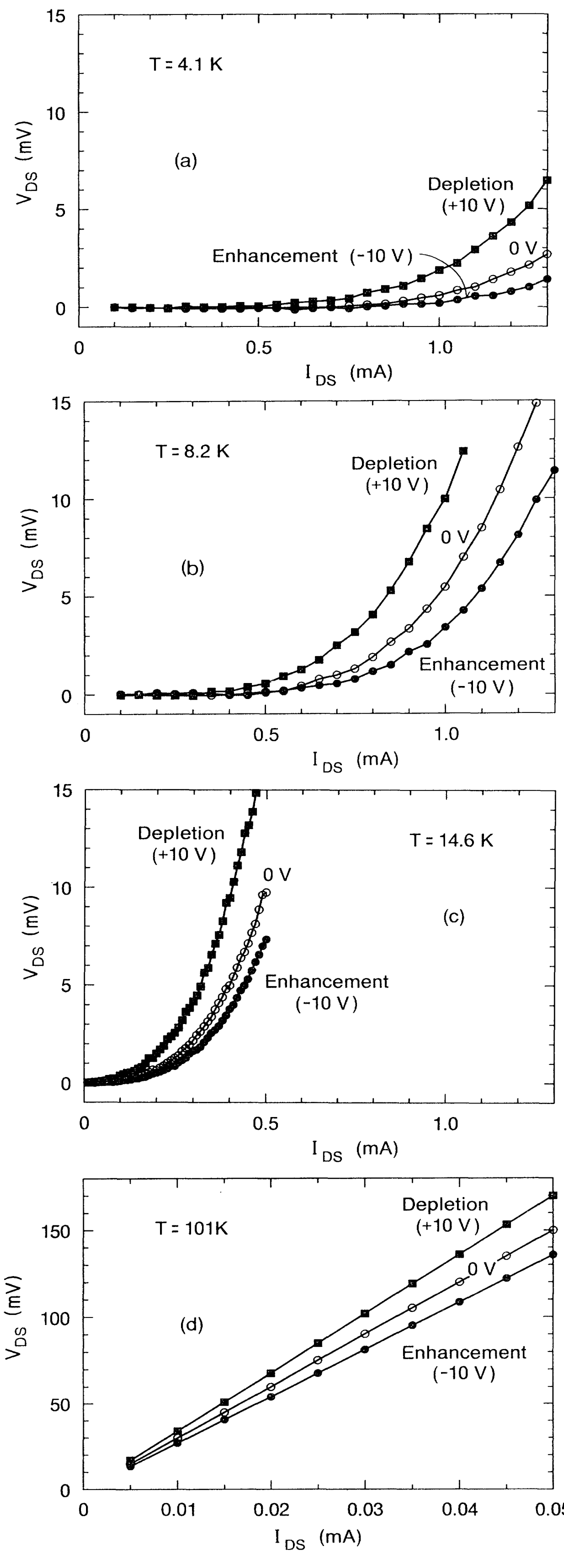

FIG. 3. Current dependence of the drain-source voltage (V_{DS}) for three applied gate voltages: $+10$ V (solid squares), 0 V (open circles), and -10 V (solid circles) at (a) 4.1 K, (b) 8.2 K, (c) 14.6 K, and (d) 101 K.

samples, this film had an average thickness of $s \simeq 70$ Å.

Figure 2 shows the temperature dependence of the normal-state resistance $R(T)$ of this sample, with 0 and ± 10 V applied to the gate electrode. As seen in this figure, upon applying the gate voltage, the $R(T)$ characteristic is changed by about $\pm 12\%$ at any temperature above $T_{c0} \simeq 14$ K with the polarity expected. Applying a positive voltage to the gate (i.e., $+10$ V) depletes the p-type $YBa_2Cu_3O_{7-\delta}$ film of holes so that its resistance increases. This polarity dependence was found in the ten samples investigated, with one exception for which a reduction of T_{c0} of about 1 K was observed in the enhancement mode as shown in the upper-left inset of Fig. 2. At higher temperatures (from a few degrees above T_{c0} to room temperature) the expected polarity dependence was observed for this sample as well.

The voltage versus current characteristic $V_{DS}(I_{DS})$ of the 70-Å $YBa_2Cu_3O_{7-\delta}$ layer is shown in Fig. 3 for various temperatures. Taking a resistance criterion of $R(100\ \mathrm{K})/10^4 \simeq 200$ mΩ for the definition of the critical current, at 4.1 K a critical current $I_c \simeq 0.85$ mA, corresponding to a critical current density of roughly $J_c \simeq 10^4$ A/cm^2, is found. Applying $+10$ and -10 V to the gate changes I_c to 0.55 and 1.0 mA, respectively.

With increasing temperature, I_c decreases to about 0.5 mA at 8.2 K [Fig. 3(b)], 0.13 mA at 14.6 K [Fig. 3(c)], and above T_c the sample is Ohmic as shown in Fig. 3(d).

To clarify whether the effect observed was not caused by the finite gate current $I_G \simeq 10$ nA, the gate was charged to ± 10 V and left disconnected from the power supply during the measurement. Since the effects described above were reproduced if a discharging of the gate to ± 5 V was taken into account, it is concluded that the gate current has a negligible influence on the effect investigated. Further experiments eliminating other potential causes of the effects observed are described in Ref. [4].

To investigate whether the effects observed result from the depinning of flux lines, from grain boundaries forming weak links, or are just artifacts from small nonsuperconducting regions in the film, $V_{DS}(I_{DS})$ characteristics were measured with magnetic fields $\mu_0 H < 8$ T applied perpendicular to the sample surface and perpendicular to the transport current. I_c drops rather slowly as a function of H. For $\mu_0 H = 8$ T, $J_c \simeq 0.2 J_c(0\ \mathrm{T})$, and, remarkably, even at these high magnetic fields J_c can be modified with the electric field. The observed $J_c(H)$ data correspond to the behavior shown by our standard 100-nm-thick $YBa_2Cu_3O_{7-\delta}$ films [5] and are not in agreement with a J_c limited by Josephson junctions, for which a much sharper drop of $J_c(H)$ is expected. Therefore we conclude that the critical current density in the sample is limited by depinning, and suggest that the gate voltage, changing the carrier concentration in the superconducting film, changes the potential well of its pinning sites.

Although it would be premature to provide a quantitative description of the observed effects, the magnitude of the induced change of the pinning force is understandable on the basis of the induced variation of the charge-carrier density: Following Ref. [4], the 24% change of the normal-state resistance when applying a gate voltage of ± 10 V (Fig. 2) is interpreted as a 24% change of the carrier density, averaged across the film volume. If, for the sake of simplicity, we estimate the carrier-concentration dependence of the pinning force $F_p(n)$ of a point defect by using isotropic Ginzburg-Landau theory, a 24% change in J_c is predicted, because $F_p(n) \propto 1/\lambda^2 \propto n$, where λ is the magnetic penetration depth. The observed change in F_p is approximately a factor of 2 higher, which is attributed to nonuniformities in the film thickness (Ref. [5]) and to a possible enhancement of pinning close to the film-substrate interface.

In summary, changes of the critical current of $YBa_2Cu_3O_{7-\delta}$ films by 50% have been induced by applied electric fields, generated by voltages of ± 10 V. The effect observed may be of interest for experiments concerning vortex pinning and flux flow in high-T_c superconductors, as well as for potential device applications of these materials.

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