Effect of dc electric field on the effective microwave surface impedance of $YBa_2Cu_3O_7/SrTiO_3/YBa_2Cu_3O_7$ trilayers

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We have studied the effect of a dc electric field on the effective microwave surface impedance of a thin film $YBa_2Cu_3O_7/SrTiO_3/YBa_2Cu_3O_7$ (YBCO/STO/YBCO) trilayer by a dielectric resonator technique. At large dc electric fields ($>10^5$ V/cm), both the effective surface resistance and reactance of the sample decrease monotonically with increasing dc voltage applied to the to YBCO film, yielding at 25 K and 24.7 GHz $|\delta R_s/\delta V_{dc}| \sim 0.25$ $\mu\Omega$/V and $|\delta X_s/\delta V_{dc}| \sim 1.8$ $\mu\Omega$/V, respectively. A two-fluid analysis indicates that the changes in the surface impedance can be explained in terms of field induced changes in the superconducting carrier density of the top YBCO film.

Epitaxial $SrTiO_3/YBa_2Cu_3O_7$ (STO/YBCO) heterostructures have been examined for use in various applications of high temperature superconducting YBCO, such as planar devices with multiple level interconnects and dielectric spacers.[1] Recently, STO/YBCO bilayers have been investigated for use in superconducting field effect transistors.[2,3] Transport measurements performed near the critical temperature of the superconducting films have shown that the effect of dc electric field on the resistance might be utilized for switching applications.[3] Also, magnetic measurements at low temperatures have provided information about the dc electric field induced changes in the kinetic inductance of superconducting films which might be useful in some SQUID applications.[4]

In principle, both the surface resistance and inductance can be modified electrically. Thus, electric field effect in superconductors might also be used in active microwave device applications such as tunable phase shifters, oscillators, and attenuators. However, unlike dc or low-frequency experiments, measurements at microwave frequencies will also sample the high-frequency properties of the gate dielectric. The relative magnitude of the effects due to the dielectric and superconducting layers is important in assessing the potential of the electric field effect in microwave device applications. In this letter, we present the results of experiments on the effect of a dc electric field on the effective microwave surface impedance Z_s of a YBCO/STO/YBCO trilayer.

The YBCO/STO/YBCO trilayer was grown *in situ* on a [001] $LaAlO_3$ substrate by pulsed laser deposition. The trilayer was deposited in ~100 mTorr of flowing O_2, at substrate temperatures of 720–780 °C, with nominal film thicknesses of ~80, ~40, and ~800 nm for the top and bottom YBCO, and the intermediate STO layer, respectively. After deposition, the top YBCO film was patterned by wet etching to form an ~90-mm^2 circular capacitor plate. X-ray analysis indicated that YBCO and STO grew epitaxially with the *c*-axis oriented normal to the substrate plane.

The transition temperature T_c for the bottom and top YBCO layers were measured to be ~88 and ~84 K, respectively. The low-frequency (120 Hz) dielectric properties of the STO layer were measured using the bottom YBCO layer and the etched top YBCO layer as capacitor plates. The results of the capacitance measurements as a function of temperature T and dc bias V_{dc} are summarized in Fig. 1. For our capacitance and microwave measurements, the top layer was grounded and the gate voltage was applied to the bottom layer. The breakdown voltage was +10 and −50 V for the forward and reverse bias, respectively. The inset shows that, at 25 K, both the dielectric constant and the dissipation factor decrease with increasing dc bias in both polarities. These results are in contrast with our earlier results in STO films where ϵ_r was found to be relatively temperature and field independent.[5] We attribute this to higher crystallinity in the current STO films: the present films have properties which resemble those of single crystal STO where much larger temperature and field induced changes in ϵ_r have been observed.[6]

The changes in the effective microwave surface impedance Z_s of the YBCO/STO/YBCO trilayer as a function of

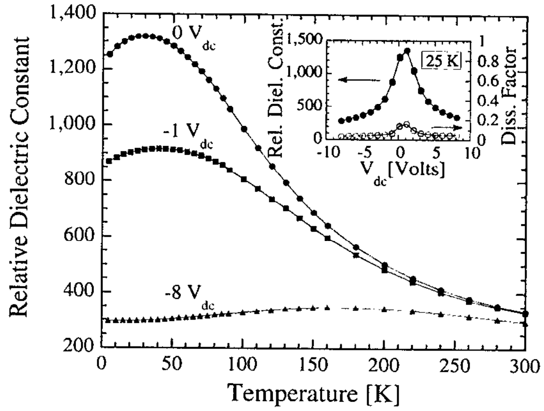

FIG. 1. Relative dielectric constant vs temperature at 120 Hz. The inset shows the dc voltage bias dependence at 25 K for both the dielectric constant and the dissipation factor.

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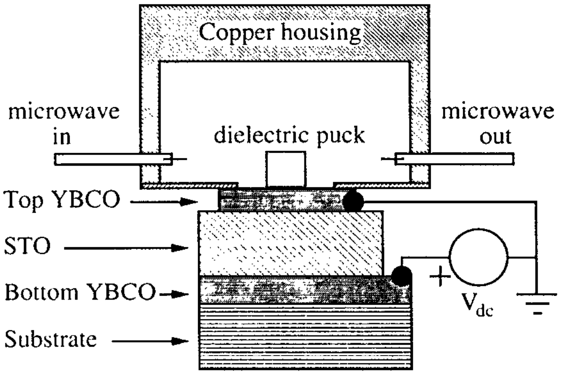

FIG. 2. Schematic of microwave measurement setup (not drawn to scale). Microwave surface impedance of the trilayer is modulated by gate voltage $V_{\rm dc}$ applied between the top and bottom YBCO layers.

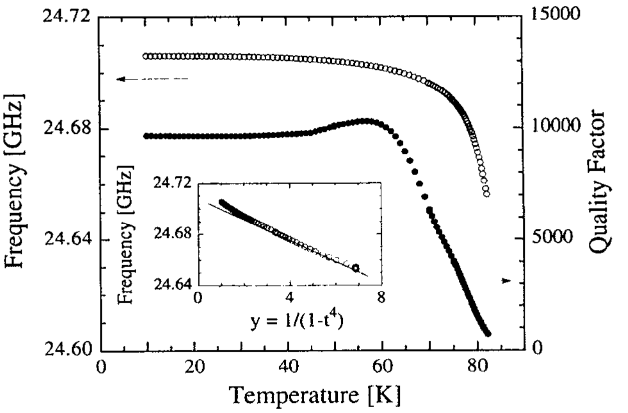

FIG. 3. Resonant frequency and quality factor vs temperature for the trilayer. Inset shows the frequency as a function of $y=1/(1-t^4)$, where t is the reduced temperature given by $t=T/85$ K.

temperature and dc electric field were measured using a dielectric resonator technique. A schematic of the experimental setup is shown in Fig. 2. In this technique, a sapphire puck is placed on the surface of a trilayer which forms an end wall of a cylindrical copper cavity. For the $\rm TEM_{01\delta}$ mode of the dielectric resonator with a resonant frequency of ~24.7 GHz, the microwave response is dominated by the trilayer sample. Thus, the measured quality factor Q is inversely proportional to the microwave energy dissipation induced in the trilayer, i.e., to the effective surface resistance R_s. Similarly, the changes in the resonant frequency f_0 are also inversely proportional to the changes in the penetration of microwave fields into the sample, i.e., to the changes in the effective surface reactance X_s. In general, changes in Q and f_0 can be related to those in Z_s of any multilayer structure provided that the microwave electric and magnetic fields can be assumed to be parallel to the surface. In a quasi-TEM approximation with $X_{\rm geo} \gg R_s$ and X_s, where $X_{\rm geo}$ is the geometric reactance of the dielectric resonator, we have[7]

$$Q \sim X_{\rm geo}/R_s, \tag{1}$$

$$\delta Q/Q \sim \delta X_s/X_{\rm geo} - \delta R_s/R_s \sim -\delta R_s/R_s, \tag{2}$$

$$\delta f_0/f_0 \sim -0.5\delta X_s/X_{\rm geo}. \tag{3}$$

From independent measurements, we find $X_{\rm geo} \sim 100\ \Omega$ at a frequency of ~24.7 GHz.

Figure 3 shows the Q and f_0 of the resonator as a function of temperature. The decrease of f_0 with temperature for the trilayer is similar to what we expect for a single layer YBCO film with $T_c \sim 85$ K and a thickness of 80 nm.[8] Thus, we conclude that the top YBCO layer dominates the frequency shift. The inset shows that the frequency shift is roughly linear with $y=1(1/t^4)$, where $t \equiv T/T_c$ is the reduced temperature and $T_c \sim 85$ K. This behavior is consistent with a simple two fluid model.[9] The thin film limit yields $X_s(t) \sim \lambda^2(t) \sim \lambda^2(0)/(1-t^4)$, where $\lambda(t)$ is the magnetic penetration depth at reduced temperature t. Thus, we obtain

$$X_s(t) \sim X_s(0)/(1-t^4). \tag{4}$$

On the other hand, the nonmonotonic changes in Q are quite different from the monotonic decrease of Q with temperature we measure for a single YBCO film.[8] Using the experimental data shown in Fig. 3 and Eq. (1), we obtain $R_s \sim 10$ mΩ for the trilayer at 25 K and 24.705 GHz.

Figure 4(a) illustrates the frequency shift and quality factor produced by the trilayer at 25 K and low dc bias voltages (±8 V). Q decreases with applied voltage in both polarities with a small offset. This response is correlated with the measured low-frequency ϵ_r decrease, and may thus originate from the changes in the dielectric properties of the STO layer. Figure 4(b) shows the effect of dc voltage on a wider range (-50 to $+10$ V) for both the low-frequency dielectric constant ϵ_r (dashed line) and the microwave response (points). For low dc bias, we observe that changes in ϵ_r are correlated to the changes in Q. However, below ~ -10 V, the changes in ϵ_r of the STO begin to saturate, and we believe that in this region the changes in the conductivity of the top YBCO layer dominate the microwave response. With voltage bias decreasing below -10 V, which corresponds to adding holes to the top YBCO layer, both Q and f_0 increase linearly.

In the following analysis, we will consider the regions in Fig. 4(b) below $V_{\rm dc} < -10$ V where changes in STO properties can be neglected, and capacitance can be assumed to be constant. From Eqs. (1)–(3) and our results from Fig. 4, we obtain $\delta R_s/\delta V_{\rm dc} \sim 0.25\ \mu\Omega/{\rm V}$ and $\delta X_s/\delta V_{\rm dc} \sim 1.8\ \mu\Omega/{\rm V}$. Using the linear fit in the inset of Fig. 3 and Eqs. (3) and (4), we obtain the effective surface reactance of the top YBCO film $X_{sy} \sim 70$ mΩ at 25 K. The peak at ~60 K for Q shown in Fig. 3 may represent the crossover temperature from dielectric to YBCO dominated loss or may result from a rather complicated interplay of leakage and dissipation of the microwave fields through the trilayer sample. Similar measurements of R_s on single films of YBCO which show comparable R_s values above 65 K give values less than 5 mΩ at 25 K. We assume this to be the upper bound for the effective surface resistance R_{sy} of the top YBCO film in the trilayer.

At 25 K, our sample is in the thin film limit where the penetration depth is much larger than the thickness of the

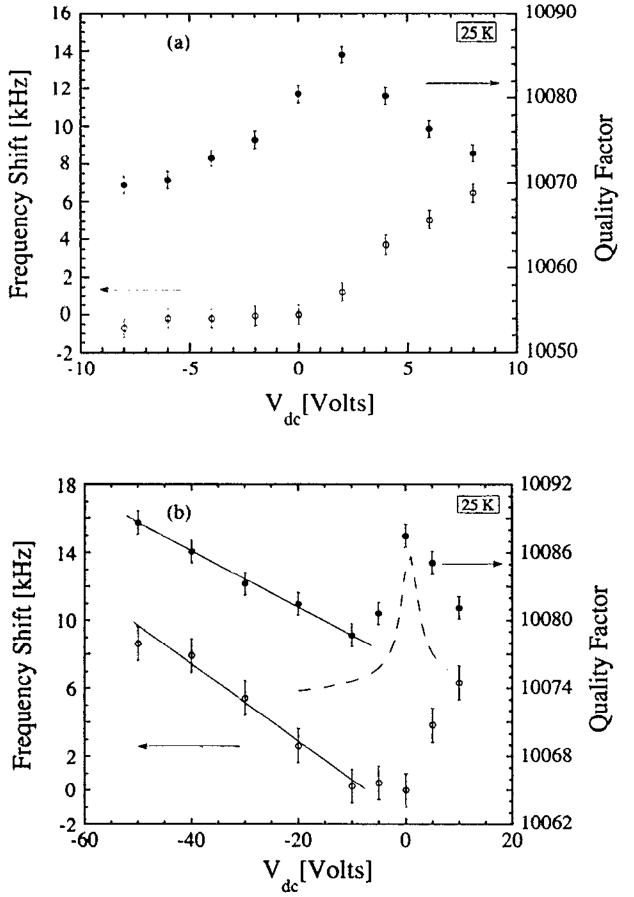

FIG. 4. Microwave response at 25 K and 24.7 GHz for (a) low dc voltage bias (± 8 V), and (b) higher dc voltage bias. The dashed line in (b) represents the relative dielectric constant ϵ_r in arbitrary units measured at 120 Hz (cf. inset to Fig. 1). The solid lines are linear approximation to the data which are used in the analysis.

superconducting film, and also $R_{sy} \ll X_{sy}$. In this case, the linear relation between the fractional changes of Z_{sy} and of density of carriers in the film simplifies to

$$\delta R_{sy}/R_{sy} \sim \delta N_n/N_n - 2\delta N_s/N_s, \tag{5}$$

$$\delta X_{sy}/X_{sy} \sim -\delta N_s/N_s, \tag{6}$$

where N_n and N_s stand for areal charge density of normal and superconducting carriers, respectively. In contrast, for dc measurements in the normal state one obtains $\delta R/R \sim -\delta N_n/N_n$.[10] From the capacitance measurements, we can calculate the induced charge density $N_{\rm int}$ at the interface of the top YBCO layer. Assuming a charge carrier density of 5×10^{21} cm^{-3} for the YBCO film, we obtain for the fractional areal charge density change per applied dc volt $(\delta N_{\rm int}/N_{\rm tot})/\Delta V_{\rm dc} \sim -3 \times 10^{-5}$ V^{-1}.

Comparison of this change with corresponding fractional changes in Z_{sy} of the top YBCO film yields $\delta X_{sy}/X_{sy} \sim -\delta N_{\rm int}/N_{\rm tot}$ and $\delta R_{sy}/R_{sy} \sim -2\delta N_{\rm int}/N_{\rm tot}$ at 25 K. The $\delta X_{sy}/X_{sy}$ result implies that roughly all the charges induced at the interface due to the applied dc electric field go into the superconducting state. If we assume that our estimate of R_{sy} is reasonably accurate, then our result for $\delta R_{sy}/R_{sy}$ further implies that the fractional changes in N_n are smaller than those in N_s. One possible explanation for the smaller fractional change in N_n is that the normal carrier density at low temperatures is dominated by nonintrinsic carriers. This might also explain why the resistive losses in these films are much higher than the predictions of a simple two-fluid theory.

In conclusion, we have observed that the microwave Z_s of YBCO/STO/YBCO trilayers can be modulated by dc electric fields through changes in the dielectric properties of STO and/or the complex conductivity of YBCO. The observed modulation of Z_s via changes in the complex conductivity of superconductivity layers can, in principle, be enhanced by reducing the thickness of the superconducting and/or insulating layers. The effect of the changes of the dielectric properties of the STO layer on the microwave response can also be enhanced in a device configuration where electromagnetic fields are concentrated within the dielectric. In that case, the dielectric losses in STO would be important for the potential of such a configuration in real device applications.[11]

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