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Tunability of Resonant Frequencies in a Superconducting Microwave Resonator by Using $SrTiO_3$ Ferroelectric Films

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An applied dc voltage varies the dielectric constant of ferroelectric $SrTiO_3$ films. A tuning mechanism for superconducting microwave resonators was realized by using the variation in the dielectric constant of $SrTiO_3$ films. In order to estimate the values of the capacitance, C, and the loss tangent, $\tan\delta$, of $SrTiO_3$ ferroelectric capacitors, we used high-temperature superconducting microwave resonators which were composed of two ports, two poles, and dc bias circuits at the zero-field points. $SrTiO_3$ ferroelectric capacitors successfully controlled the resonant frequency of the resonator. Resonant frequencies of 3.98 GHz and 4.20 GHz were measured at bias voltages of 0 V and 50 V which correspond to capacitance values of 0.94 pF and 0.7 pF, respectively. The values of the loss tangent, $\tan\delta_{eff}$, obtained in this measurements, were about 0.01.

I. INTRODUCTION

High-frequency and high-speed devices have received extensive attention due to potential applications in the information and telecommunications market. Combining thin-film ferroelectric (FE) materials with thin-film high-temperature superconductors (HTS) allows to use both the nonlinear dielectric properties of FE materials for high speed and voltage tuning and the low conductive loss of HTS films to reduce the insertion loss [1,6]. These tunable devices are useful in several communication applications, such as a phased-array antenna systems and frequency agile microwave devices, for example, tunable filters which are useful for eliminating interference from a variety of sources.

Using the multilayer structure $YB_2Cu_3O_{7-\delta}/SrTiO_3$ (YBCO/STO) on a $LaAlO_3$ substrate, we observed a high-frequency dielectric behavior for the FE thin films and a tunability of 2 when the applied bias was varied from 0 V to 60 V and the loss tangent was in the low 10^{-2} range at 77 K [2]. The microstructures of the interfaces in the YBCO/$KTaO_3$ epitaxial multilayers, as well as the permittivity ϵ and the dielectric loss of the FE $KTaO_3$ film, are reported in Ref. 3.

The present work includes measurements of the microwave properties of FE STO films by using a high-temperature superconducting microwave resonator. The results indicate the possiblity of the Q-factors being high enough and the tunability being large enough for practical applications in tunable microwave devices [4,5].

II. EXPERIMENT

Fig. 1 shows the layout for investigating of the microwave properties of a resonator with a FE capacitor. The resonator consists of two ports and two poles. The two poles are aligned and broken by a small gap, 1 mm, at which a planar FE capacitor is located to control the resonant frequencies of the resonator. This FE capacitor is prepared separately and attatched to the gap. The bias-voltage points are determined by highly decoupling the points of the poles, and the bias-circuit points are designed on the same plane as the low-pass filters. Fundamental frequency responses of the resonator can be simulated by varying the microstrip length of the resonator.

Sapphire substrates are chosen as the best candidates for fabricating YBCO/CeO_2 and YBCO/STO multilayers due to their excellent microwave properties. The Al_2O_3 (r-cut) substrates with a 1 mm-thickness are covered by a CeO_2 film which acts as a buffer layer. The YBCO films are deposited subsequently on the buffer-layered substrate. CeO_2 and YBCO films with thicknesses of 20 nm and 500 nm, respectively, are prepared by a pulsed-laser-deposition (PLD: KrF; 248 nm) system. These films are deposited in-situ under an O_2 environment (CeO_2: 200 mTorr, YBCO: 400 mTorr) and the same substrate temperature (780°C) to get high-quality films with uniform, large areas [7]. After deposition, the YBCO films are patterned by photolithography and the residues are removed by dry etching. As electrodes, gold films are made by dc-sputtering. For the ground plane, gold film is deposited on the opposite side of the sub-

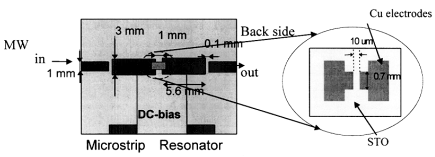

Fig. 1. Layout of the YBCO resonator with a FE STO capacitor. The FE STO capacitor with Cu electrodes was prepared separately and attached to the center gap of the YBCO resonator.

strate.

FE STO film which acts as a capacitor is prepared by PLD, at a substrate temperature of 730°C in an oxygen atmosphere of 100 mTorr with a laser energy density of 1.2 J/cm^2. The growth of the FE STO film is checked by X-ray diffraction (see Fig. 2). A 300-nm-thick FE STO layer on a $LaAlO_3$ substrate is covered by a 3-μm-thickness Cu film for electrodes. Fig. 1 includes the structure of the STO capacitor whose size is 1×2 mm^2. Fig. 3 shows a side view with more detailed structure, of the resonator with a planar FE STO capacitor. The gap distance between the two electrodes of the capacitor is 10 μm. The capacitor has a capacitance of ~0.4 pF and a loss tangent of 0.001 at a 10-kHz frequency. These values are determined by a HP4284A LCR meter at room temperature. The values of the capacitance depend on the applied microwave frequencies, temperatures, and dc bias voltages.

III. RESULTS AND DISCUSSION

Using the HP8510C network analyzer, we measured microwave frequency responses of the resonator. Copper packages are used for microwave measurements. For impedance matching [4], 50-Ω SMA connectors are used during the experiment. All measurements are done at liquid-nitrogen temperature to keep the superconductivity of the YBCO film. Fig. 4 shows the simulated data of the resonator for several capacitance values: 0.1, 0.3, 0.5, and 0.7 pF. This simulation is done by using compact software [8]. In Fig. 5, the frequency response of the $YBCO/CeO_2/\alpha$-Al_2O_3 resonator shows a-0.94-dB insertion loss at a 5.525-GHz center frequency without the FE STO capacitor, 5.525 GHz being an immovable frequency mode (the 2nd mode: even mode) of this resonator. For the 2nd mode, there is a current node at the position of the STO capacitor. This mode is, therefore, unaffected by the properties of the STO capacitor. This frequency is determined by the length of a pole in the resonator. The loaded quality factor (Q_L) of this resonator is 80, and the unloaded quality factor (Q_u) is 780.

Fig. 6 shows the frequency response of the resonator with the FE STO capacitor. 5.525 GHz is an immovable frequency mode of this resonator, and the other frequencies, in Fig. 6, are the movable frequency modes. According to the strength of the applied dc voltages, movable frequency modes changes, for example, 3.98 GHz at zero bias voltage and 4.20 GHz at 50 bias voltage. Movable frequencies are determined from the length of the two poles connected by the STO FE capacitor. From Fig. 6,

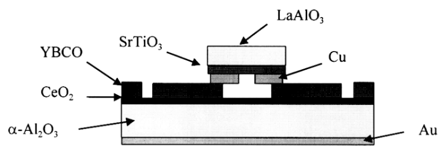

Fig. 3. Side view of the tunable resonator.

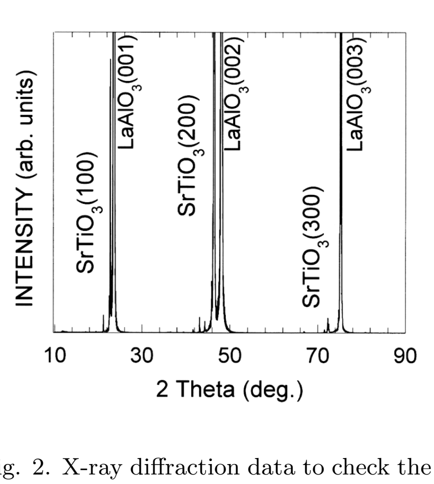

Fig. 2. X-ray diffraction data to check the crystallography of the FE $SrTiO_3$ film on a $LaAlO_3$ substrate.

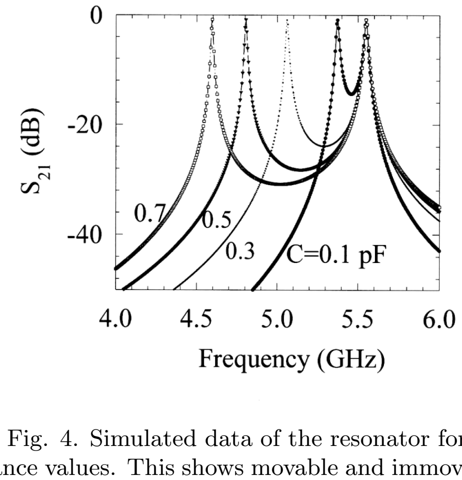

Fig. 4. Simulated data of the resonator for several capacitance values. This shows movable and immovable frequencies simultaneously and was simulated by compact software.

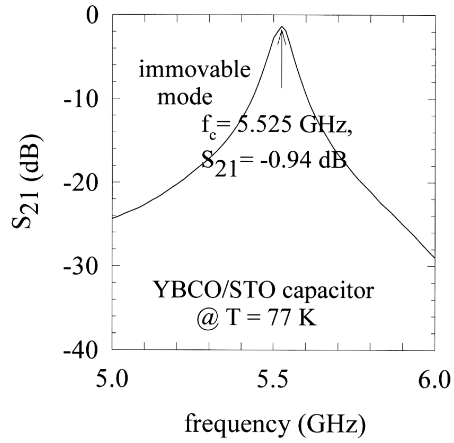

Fig. 5. Microwave frequency response of the immovable mode of a YBCO/CeO_2/α-Al_2O_3 resonator.

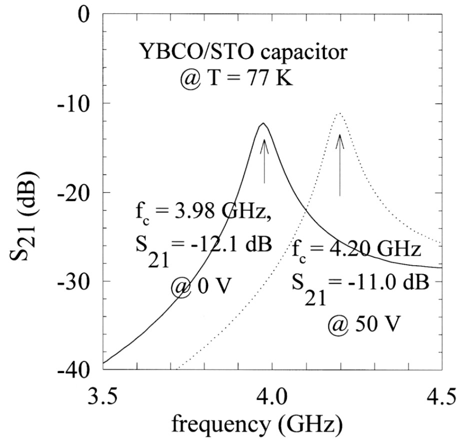

Fig. 6. Microwave frequency response of a YBCO/CeO_2/α-Al_2O_3 tunable resonator with a STO FE capacitor. The resonance peaks at 3.98 GHz and 4.20 GHz are for bias voltages of 0 V and 50 V, respectively.

these resonant frequencies have almost the same quality factor: Q_u=60. As the bias voltage increases from 0 V to 50 V, the movable resonant frequencies are increased by 220 MHz, that is, from 3.98 GHz to 4.20 GHz. This fact shows that the dielectric constants of STO FE film reduce as the bias voltages increase.

The measurements of the movable resonant frequency ω_r and the unloaded quality factor Q_u of the tunable resonator with a FE capacitor allow us to calculate the values of the capacitance and the effective loss tangent, $\tan\delta_{eff}$, of the FE capacitor by using the following relations [2,3]:

$$C = \frac{\tan\varphi}{2Z_0\omega_r}, \qquad \varphi = \pi\frac{\omega_r}{\omega_2}, \tag{1}$$

$$\tan\delta_{eff} = \frac{l}{\xi}\left(\frac{l}{Q_U} - \frac{l}{Q_0}\right), \qquad \xi = \frac{2}{1 - 2\varphi/\sin 2\varphi}. \tag{2}$$

Z_0 and φ are the characteristic impedance and the electrical length of the resonator. ω_2 and Q_0 are the immovable frequency and the unloaded quality factor of the resonator with a capacitor without dielectric loss, which is called a standard planar capacitor, based on materials with small $\tan\delta$ on a substrate $LaAlO_3$. ξ is the inclusion factor which reflects the ratio of the stored energy in the capacitor to the stored energy in the capacitor and resonator; *i.e.*, $\xi = W_c/(W_l + W_c)$, where W_c and W_l are the electrical energies stored in the capacitor and in the microstrip part of the resonator. Considering the non-dispersion of the substrates, α-Al_2O_3, $LaAlO_3$, in this range of frequencies, we measured the value of the capacitance with standard capacitors by using an LCR meter at room temperature in order to determine the capacitance values of the FE STO capacitors from the measurements of the resonant frequency. Also, the measurements of the resonant frequency with standard capacitors give the unloaded quality factor, Q_0, which is used in Eq. (2) to calculate the loss tangent, $\tan\delta_{eff}$ of the FE capacitors.

The above calibrations using many standard capacitors with different electrode geometries are necessary in order to improve the accuracy of C and $\tan\delta$ measurements. The capacitance values at the resonant frequencies are 0.94 pF and 0.7 pF, while the value of the loss tangent, $\tan\delta$, is about 0.01 on the basis of the calibration of the capacitor and the resonator.

IV. CONCLUSIONS

The microwave frequency characteristics of superconducting tunable resonators are considered using the variation in the dielectric constant of ferroelectric materials under the influence of an applied dc voltage. Movable resonant frequencies are measured at 3.98 GHz and 4.20 GHz for dc bias voltages of 0 V and 50 V, respectively. The values of the capacitance and the loss tangent of the $SrTiO_3$ ferroelectric capacitor are 0.94 pF and 0.7 pF, and about 0.01 at those frequencies. The resonant frequencies of the resonator with $SrTiO_3$ ferroelectric capacitors are successfully controlled at each voltage. Therefore, this demonstrates the possibility of estimating the values of the capacitance and the loss tangent by using the applied voltage and tuning the resonant frequencies of the resonator.

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