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Microwave properties of pulsed-laser $SrTiO_3$ thin films at low temperatures

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Abstract

Properties of $SrTiO_3$ thin films were characterized under the influence of an applied dc voltage utilizing a gold resonator with a flip-chip capacitor. The measurements were performed at microwave frequency ranges and low temperatures cryogenic temperatures. The dielectric constant of 830 and the low loss tangent of $6X10^{-3}$ at 3.64 GHz were observed at 90 K and 100 V. The quality in the $SrTiO_3$ film was presented in terms of fractional frequency under the bias voltages and cryogenic temperatures.

Keywords : Ferroelectric thin film, $SrTiO_3$, dielectric loss, flip-chip technique.

I. Introduction

Since high T_c superconducting thin films have demonstrated low surface resistance at microwave frequency ranges,[1] recent advance of ferroelectric (FE) thin films[2]-[10] has increasingly stimulated significant potential for the commercialization of microwave tunable devices, such as tunable filters and phased array radar systems. In the FE film, electronic tunability of the operation frequency is related to the nonlinear dielectric constant, which can be tuned by an applied bias voltage. The dielectric loss plays a crucial role in determining the performance of electrically tunable devices, which requires low loss tangent in the GHz regime. In order to integrate high T_c superconducting thin films for high frequency systems, the dielectric properties of the FE film must be resolved at low temperatures, together with voltage or field dependence of the FE films. Therefore, in this letter, microwave dielectric properties in the STO film deposited on a $LaAlO_3$ (LAO) substrate are presented. Dielectric constant and loss tangent, $\tan\delta$, of the STO film were presented as a function of bias voltages at cryogenic temperatures and at about 3.64 GHz.

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II. Experiments

The STO films were deposited *in situ* on LAO substrates utilizing a pulsed laser deposition system (PLD). The deposition condition and sample preparation were in detail described in reference. Microwave responses of the resonator with a capacitor were measured using a Hewlett-Packard (HP) 8510C network analyzer. The capacitance of a standard capacitor was separately measured by using a HP 4284A precision LCR meter at 1 MHz. of the corresponding author.

Figure 1 shows typical top and side views of the gold resonator and the planar capacitor. The resonator was designed to achieve a movable mode at 3.64 GHz that had the capacitance dependence at the gap of center microstrip line and an immovable mode at 5.6 GHz. Figure 2(a) shows typical transmission coefficient (S_{21}) of the gold resonator without having a flip-chip capacitor at 90 K. In order to estimate capacitance values and loss tangents of the STO film

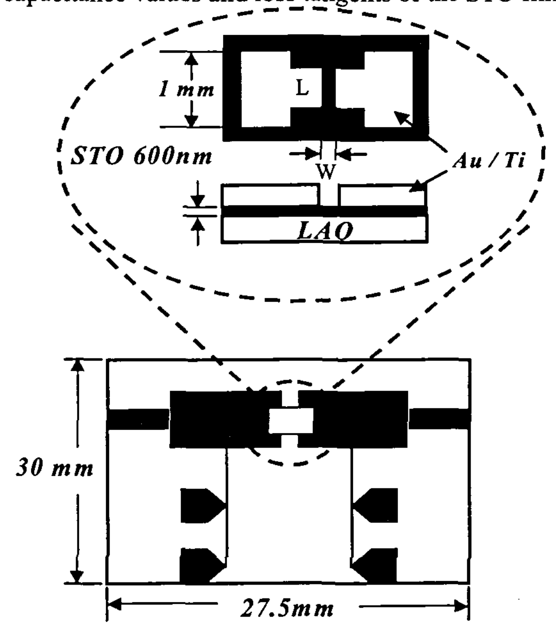

Fig. 1 Typical views of the gold resonator and the planar capacitor, where the planar flip-chip capacitor was located at the break point in the microstrip-line.

at about 3.64 GHz, the calibration sheet of the resonator was at first determined from the measurements of the resonant frequency and the capacitance. The measurements were carried out using several standard Au/LAO capacitors that did not have the STO film. The standard capacitors with different dimensions exhibited the values of 0.502, 0.451, 0.43, 0.358, 0.354, and 0.309 pF, respectively. The capacitance values were obtained at 1 MHz using the HP 4284A LCR meter at room temperature. These values corresponded to the resonance frequencies of 4.41, 4.48, 4.51, 4.58, 4.63, and 4.71 GHz in the resonator, respectively when the microwave measurements were done using the same standard capacitors. The movable resonance frequency (ω_r) and the capacitance (C) are given by the following relations[6].

$$C = -\frac{\tan\varphi}{2Z_o\omega_r} - C_o, \quad \varphi = \pi\frac{\omega_r}{\omega_2} \qquad (1)$$

where Z_0 and C_0 are the characteristic impedance and the parasitic capacitance of the microstrip line, respectively. The ω_2 was the immovable resonance frequency.

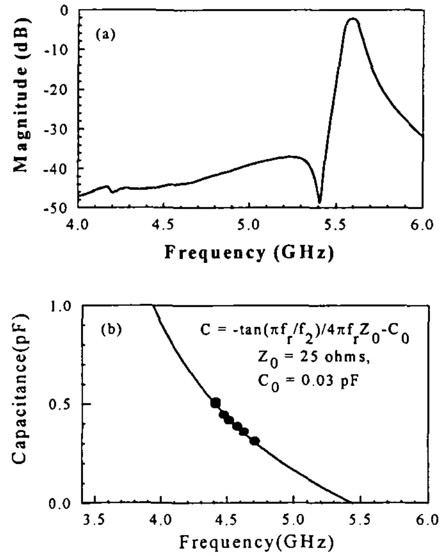

Fig. 2 (a) Typical transmission coefficients (S_{21}) of the gold resonator at 90K, and (b) calibration sheet of the resonator. All the data were obtained by using standard capacitors with slightly different dimensions. The STO film was not included in the standard capacitor.

Experimental data of capacitance versus movable frequencies were fitted to the equation (1) to estimate the values of Z_0 and C_0. The values of Z_0 and C_0 were 25 Ω and 0.03 pF, respectively. Figure 2(b) shows the calibration sheet of the resonator in the frequency ranging from 3.5 GHz to 6 GHz. In addition, the quality factor (Q_0) values were estimated from the resonance peaks. The average Q_0 value in our standard capacitors was found to be about 200.

Figure 3(a) exhibits typical resonance peaks measured by using a STO capacitor at different bias voltages and at 90 K. The resonant frequencies in the movable mode shifted to high frequency side with increasing bias voltages, while the immovable mode at 5.6 GHz remained fixed. Similar shift behavior of the resonant frequency was observed with increasing temperatures in our experiments, not shown in the Fig. 3(a). Figure 3(b) displays fractional shifts in the resonant frequency with increasing bias voltages at different temperatures. All the frequency tuning was clearly observed over cryogenic temperatures ranging from 55 K to 130 K reproducibly. Frequency shift

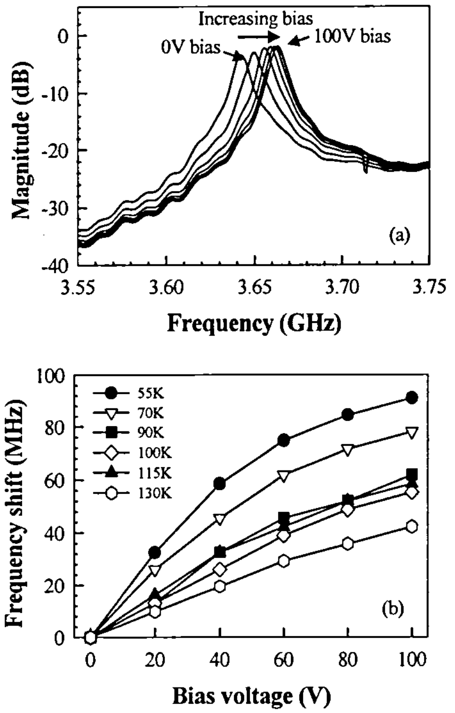

Fig. 3 (a) Resonance peaks measured using the STO capacitor at different bias voltages, and (b) fractional shifts in the resonant frequency as a function of bias voltages under cryogenic temperatures.

greater than 60 MHz at 90 K and 100 V was obtained at around 3.64 GHz frequency.

Figure 4(a) shows bias voltage dependence of the dielectric constant at various temperatures ranging from 55 K to 130 K. The dielectric constant of the STO film was calculated from the capacitance values using the following relation.

$$\varepsilon = 4C\frac{(Ln2 + \pi W/4H)}{\pi \varepsilon_o L} \qquad (2)$$

where C is the capacitance value and W and L are the width and the length of capacitor gap structure, respectively (W=6 um, and L=7 mm), and H is the thickness of the STO film. Small electrical tunability of our STO film was observed at about 3.64 GHz. A closer inspection of the dielectric constant revealed the value of 860 at around 115 K, compared with that at other temperature range. This large dielectric constant is likely correlated to the structural phase-transition that takes place at 115 K. It is known that the phase-transition temperature shifts towards higher temperatures with the increasing operation frequency. Figure 4(b) plots measurements of the dielectric loss in the STO film as a function of bias voltages at about 3.64 GHz. The loss tangent of the STO film was calculated using the following equations[13].

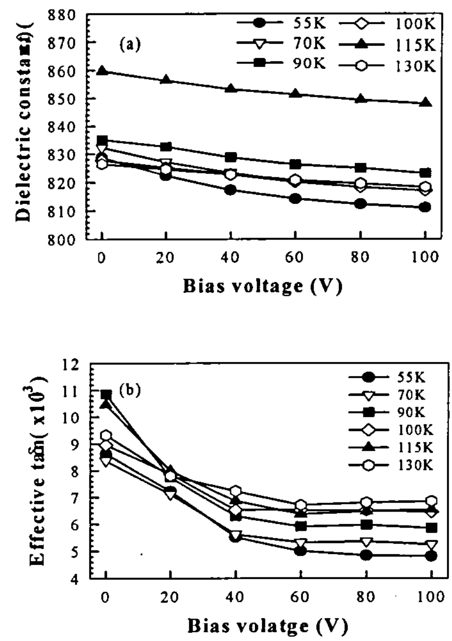

Fig. 4 (a) Bias voltage dependence of the dielectric constant, and (b) dielectric loss in the STO film at temperatures ranging from 55 K to 130 K and at about 3.64 GHz.

$$\tan\delta = \xi^{-1}(Q_u^{-1} - Q_o^{-1}),\ \xi = \frac{2}{1-2\varphi/\sin\varphi},\ \varphi = \pi\frac{\omega_r}{\omega_2} \qquad (3)$$

where Q_u is the unloaded Q-factor of the resonator with a capacitor having the STO film and Q_0 is the unloaded Q-factor of the resonator with a capacitor without having the STO film. As shown in Fig. 4(b), the loss tangent of our STO film was on the order of 10^{-3} at about 3.64 GHz. However, the dielectric loss was still larger. It is likely due to lattice-mismatch or interface loss between the STO film and the LAO substrate, resulting in stress or interfacial charging effect between them. The loss tangent had the order of less than $6X10^{-3}$ at 90 K and 100 V. In addition, the loss peak moved to higher temperatures as the frequency increases. We expect that the shift in the loss peak was associated with a thermally activated barrier[14] or cubic to tetragonal structural phase-transition,[5] as explained in Fig. 4(a).]

III. Summary

Microwave properties of the STO thin film were characterized using a gold resonator with a planar STO capacitor. Experimental results indicate reasonable dielectric constant of 830 at 3.64 GHz and structural phase transition at around 115 K, even though some uncertainty or assumption in the measurement process appears. The loss of $6X10^{-3}$ at 3.64 GHz was obtained at 90 K and 100 V.

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