Voltage and Frequency Dependent Dielectric Properties of BST-0.5 Thin Films on Alumina Substrates

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***Abstract*—Dielectric properties of $Ba_{0.5}Sr_{0.5}TiO_3$ (BST-0.5) polycrystalline thin films, deposited on alumina substrates by means of reactive Pulsed Laser Deposition (PLD), were measured at GHz frequencies using an interdigital capacitor (IDC). By applying a voltage up to 40 V between the two groups of fingers at room temperature, a high tunability of ∼27% was achieved at 5 GHz. A relative dielectric constant of ∼500 (consistent with the low-frequency IDC measurements) has been obtained using coplanar wave guides by means of the Through-Reflect-Line (TRL) analysis combined with either a conformal mapping model or a full wave calculation. The BST loss tangent was estimated as ∼0.05 in the range 3–16 GHz.**

***Index Terms*—BST, coplanar waveguide (CPW), device characterization, ferroelectric thin films, interdigital capacitor (IDC), tunability.**

I. Introduction

The DC tuning voltage of ferroelectric-based microwave components makes it possible to create a new class of versatile, low-loss, low-cost and compact microwave components such as frequency-agile filters, [1] tunable delay lines and phase shifters [2]. All these devices can be realized with structures based on ferroelectric thin films that produce internal electric polarization changes with an externally applied electric field [3], [4]. One of the most attractive ferroelectric materials suitable for high performance microwave applications is Barium-Strontium-Titanate $Ba_xSr_{1-x}TiO_3$ (BST), which has a high tunability $(\Delta\varepsilon/\varepsilon)$, high dielectric constant and relatively low loss tangent at microwave frequencies [5]. As a first step toward such applications, broadband material characterization of BST at microwave frequencies should be addressed.

To this end, we have developed two complementary diagnostics, in combination with appropriate analytical and numerical models. The first makes use of thin film interdigital capacitors (IDC) to measure the capacitance of the device for various applied electric fields. The second diagnostic enables the extraction of the propagation constant of a coplanar waveguide (CPW) transmission line. Models were then used to link measurements with the dielectric constant of the BST thin film. The main interest of IDCs is that, for a voltage in the range 0–40 V applied between the two groups of fingers, large electric fields can be induced in the BST layer due to the small spacing between the fingers (∼8 μm). The relative complexity of the IDC geometry makes IDC full-wave modeling very challenging and one must rely in practice on simpler quasistatic or semi-empirical models. On the other hand, the simplicity of the CPW geometry does permit, in principle, a more accurate characterization of its microwave properties. Unfortunately, the effect of the applied voltage could not be investigated with CPWs because of their larger spacing between electrodes (∼100 μm).

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II. Fabrication

We have deposited BST-0.5 thin films on polycrystalline Al_2O_3 using reactive Plasma Laser Deposition (PLD). A KrF laser beam (0.8 J/cm^2) was focused on the 99.9% pure BST-0.5 target with an oxygen background pressure of 5 mtorr and a deposition temperature of 600 °C. A final annealing in a furnace at 800 °C in oxygen is used to enhance the crystallinity of the films. X-Ray diffraction $\theta/2\theta$ spectra showed that the BST thin films obtained are polycrystalline, with a structure very close to the standard polycrystalline-BST-0.5 [6].

For the fabrication of the IDC and CPW, we developed a bilayer lift-off process. LOR20B resist was used in combination with a conventional positive resist in order to obtain a 1 μm undercut over a 2.5 μm thickness and thus allowing a metallic film pattern of up to ∼1 μm thick. The coplanar devices are made of evaporated Cu with a thin Ti adhesive layer.

III. Results

In both devices (IDC and CPW) a 1.8 μm BST layer lies between an alumina substrate of 250 μm and a Cu layer of ∼0.4 μm with the appropriate patterning. Measurements were performed using a HP8510C network analyzer calibrated with a Through-Reflect-Line (TRL) kit patterned on the substrate. For the IDC diagnostic, the capacitance has been obtained from the measured reflection coefficient S_{11}. For the CPW, the complex propagation constant was obtained directly from the multi-line TRL calibration procedure [7].

The modeling and design of the IDC and CPW were made using a conformal mapping method (CMM) in combination with the partial capacitance technique [8], [9]. This method consists in splitting the multilayered substrate into several single layer regions of modified permittivity and then to apply

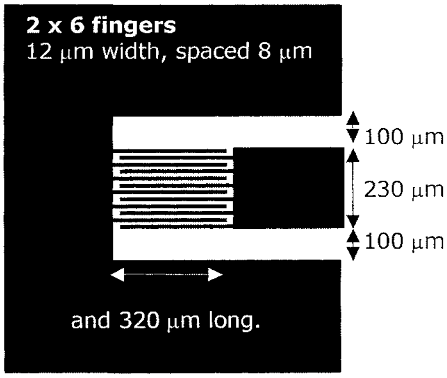

Fig. 1. IDC used in the capacitance measurements.

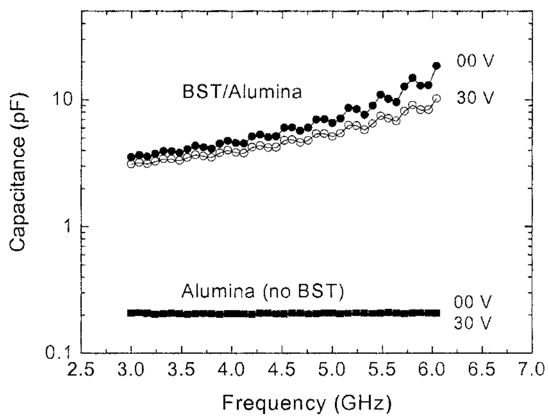

Fig. 2. Measured IDC capacitance of BST thin films (1.8 μm) deposited on alumina (250 μm) as a function of frequency, at 0 and 30 V applied voltage. Substrate measurement is also shown.

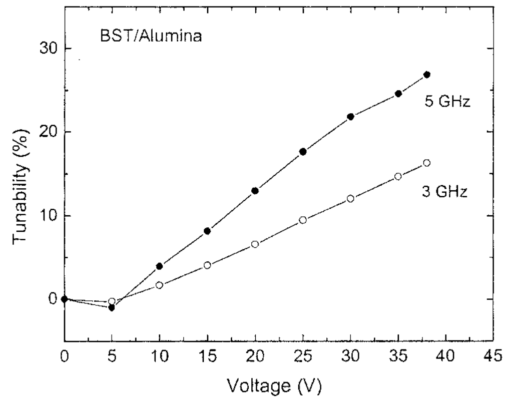

Fig. 3. Measured IDC tunability ($\Delta\varepsilon_2/\varepsilon_2$) as a function of the applied voltage at 3 and 5 GHz.

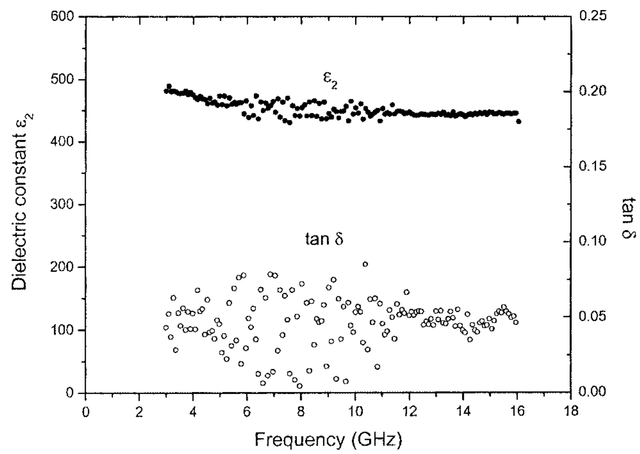

Fig. 4. Dielectric constant and loss tangent of the BST thin film obtained using the TRL method and a conformal mapping model for the coplanar wave guide.

conformal mapping to each separate region into a simple parallel-plate capacitor. The capacitance of the latter is the sum of the capacitances of the partial regions and can be expressed as $C = \varepsilon_0\varepsilon_{eff}G_0$, where

$$\varepsilon_{eff} = 1 + G_1(\varepsilon_1 - 1) + G_2(\varepsilon_2 - \varepsilon_1) \qquad (1)$$

is the effective dielectric constant. Here ε_1 and ε_2 are the substrate and BST dielectric constants respectively, while G_0, G_1 and G_2 are geometrical factors.

The chosen geometry of the IDC device is illustrated in Fig. 1. Fig. 2 shows the measured capacitance of the IDC as a function of the frequency for various applied voltages. The measured alumina capacitance without BST is in excellent agreement with the value of ~0.2 pF calculated using the CMM and the dielectric constant $\varepsilon_1 = 9.8$ found in the literature. The BST layer increases the capacitance of the device by a factor of 10–100 depending on the frequency. The increase of the capacitance with the frequency is mainly due to an LC resonance of the device at the frequency $f \sim 7$ GHz and not specifically to the frequency behavior of the BST layer. Using the measured capacitance and the CMM, we found that the BST dielectric constant is $\varepsilon_2 = 500$–600 at low frequency and ~2000 at 6 GHz. The BST tunability $(\Delta\varepsilon_2/\varepsilon_2)$ as a function of the applied voltage is shown in Fig. 3. One observes that the tunability is approximately a linear function of the voltage above 5 V and reaches a maximum of 27% at 38 V and 5 GHz.

The CPW used are 6 mm and 9 mm length. As in the IDC geometry, shown in Fig. 1, the center strip width is 230 μm and the ground planes are separated from the central strip by 100 μm. The dielectric constant ε_2 (and thus the loss tangent) of the BST layer as a function of the frequency can be obtained by using $\varepsilon_{eff} = -\gamma^2c^2/\omega^2$ [10], where γ is the measured propagation constant, in combination with (1). Losses in conductors have been considered small with respect to the losses in the BST layer [11]. The results are shown in Fig. 4. The dielectric constant obtained is consistent with the results inferred from the IDC at low frequency. The loss tangent is observed to take the average value of ~0.05 in the whole frequency range of interest. For the CPW, we have also calculated $\beta = \mathrm{Re}(\gamma)$ as a function of frequency by using a full-wave Method of Lines (MoL) [12] and compared it with the result of the TRL analysis. Without BST, the agreement was found to be excellent using $\varepsilon_1 = 9.8$. With BST, measurements follow closely the calculated (nearly constant) function $\beta(f)$ corresponding to the BST dielectric constant $\varepsilon_2 \sim 500$, in agreement with the two other aforementioned estimates.

IV. CONCLUSION

This paper has reported original measurements of the dielectric constant and loss tangent of $Ba_{0.5}Sr_{0.5}TiO_3$ thin films obtained by pulsed laser deposition on polycrystalline alumina substrate. A high tunability of ∼27% has been achieved at 38 V and 5 GHz. The strong frequency-dependence of the dielectric constant observed for the chosen IDC geometry (500 to 2000 in the range 3–6 GHz) is due to an LC resonance of the device near 7 GHz and not specifically to the BST layer. In the case of the CPW, a frequency independent dielectric constant of ∼500 and a loss tangent of ∼0.05 have been obtained in the range 3–16 GHz in good agreement with the measurements performed on the IDC at low frequency.

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