Tunable Barium Strontium Titanate Thin Film Capacitors for RF and Microwave Applications

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***Abstract*—The measurement results for thin film barium strontium titanate (BST) based voltage tunable capacitors intended for RF applications are reported. At 9 V dc, BST capacitors fabricated using MOCVD (metalorganic chemical vapor deposition) method achieved 71% (3.4 : 1) tunability. The measured device quality factor (Q) for BST varactors is comparable with the device Q for commercially available varactor diodes of similar capacitance. The typical dielectric loss tangent was in the range 0.003–0.009 at VHF. Large signal measurement and modeling results for BST thin film capacitors are also presented.**

***Index Terms*—Barium strontium titanate, (Ba, Sr)Ti0$_3$, BST, ferroelectric, MOCVD, thin film, tunable capacitor, varactor.**

I. Introduction

THIN film barium strontium titanate (BST) is a ferroelectric material, which has shown great promise for the fabrication of tunable RF and microwave components, such as voltage-controlled oscillators, tunable filters, and phase shifters [1]–[4]. The dielectric permittivity of BST can be tuned via an applied dc electric field. In parallel plate capacitors, tunabilities greater than 50% are achievable at dc bias levels as low as 2–5 V [5], [6]. By varying the film thickness, a wide range of operating voltages can be accommodated. The high dielectric constant of BST thin films (typically around 300 at room temperature) allows the fabrication of high capacitance density capacitors.

Varactors based on BST thin films offer the advantages of integratability, low cost, low voltage tunability and high speed. Tunable BST capacitors do not produce junction noise in comparison with the reverse biased junction in varactor diodes and in general, varactor diodes tend to be lossy at RF and microwave frequencies [7], [8]. In order for a BST capacitor to be a viable replacement for varactor diodes, there are several issues that must be addressed. For example, the design of wideband and low loss tunable RF components using BST varactors requires detailed characterization of the frequency and the field dependence of both the permittivity (tunability) and the dielectric loss tangent of BST.

Manuscript received July 16, 2001; revised October 19, 2001. The review of this letter was arranged by Associate Editor Dr. Shigeo Kawasaki.

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Publisher Item Identifier S 1531-1309(02)00861-9.

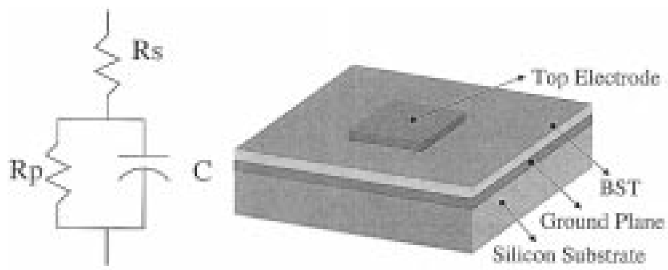

Fig. 1. Schematic illustration of a planar BST thin film capacitor with Pt electrodes and the associated circuit used to model the measured data.

In the light of these comments, this paper discusses the measurement results for parallel plate BST capacitors. In particular, the dielectric properties of BST thin films in parallel plate capacitors have been measured, and an investigation of different loss contributions to the device quality factor has been conducted. In addition, the effect of large RF voltages on the tunability of the BST capacitors is presented.

II. Capacitor Measurements and Modeling

Parallel plate capacitors were fabricated on 500 μm thick silicon wafers covered with approximately 500 Å of thermal SiO_2 and a final 1000 Å of Pt (this Pt layer acts as the device ground plane—see Fig. 1). $(Ba_{0.7}Sr_{0.3})TiO_3$ was grown by metalorganic chemical vapor deposition (MOCVD) method to thicknesses between 500 and 5000 Å. MOCVD is the deposition method of choice for the fabrication of BST thin films. It provides excellent composition control, large area coverage, and the potential for areal homogeneity and conformal coating of complicated topographies [9], [10]. In this work, all BST films were uniformly deposited on 150 mm wafers, thus indicating the suitability for commercial mass production. Top electrodes, completing the parallel plate capacitor structure, were deposited by either sputtering or electron-beam evaporation up to 3000 Å thickness. The dielectric loss tangent and BST tunability were determined based on the impedance measurements for various size capacitors. The BST capacitors are modeled in terms of an equivalent circuit shown in Fig. 1. In this model, R_S accounts for the conductor losses, and R_P accounts for the BST losses. Since the conductor thickness deposited in the fabrication of the BST capacitors is much smaller than the skin depth at the frequencies of interest, R_S is assumed to be frequency independent. The loss tangent of the BST is also assumed to be constant over this frequency range [5], [10]. The element values of the equivalent circuit model were optimized such that the modeled

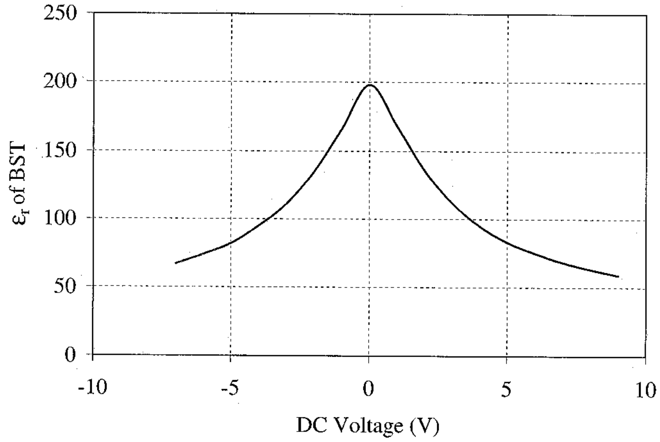

Fig. 2. Relative permittivity vs. applied dc voltage between 45 and 500 MHz (The BST thickness is 700 Å and the top electrode size is 50 × 50 μm^2).

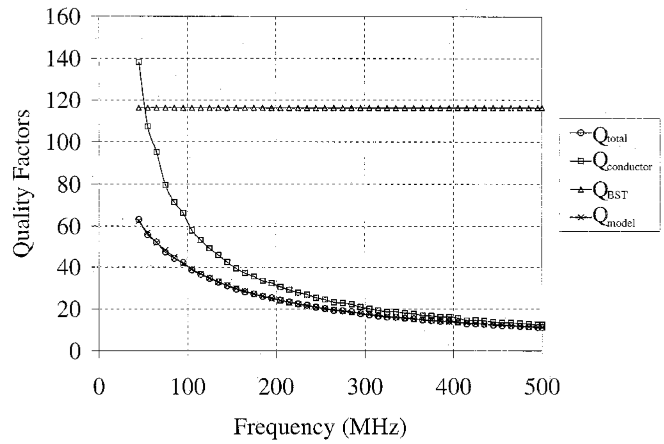

Fig. 3. Quality factors, Q_{total}, $Q_{\rm BST}$, $Q_{conductor}$, Q_{model} for a 65 pF capacitor at 0 V dc bias.

and measured S-parameters fit over 45 to 500 MHz. The relative dielectric constant (ε_r) and the loss tangent ($\tan\delta$) of the BST thin films were then calculated using the following relations

$$\varepsilon_r = \frac{C \cdot d}{\varepsilon_0 A} \quad (1)$$

$$\tan\delta = \frac{1}{\omega R_P C} \quad (2)$$

where C is the capacitance, A is the top plate area of the BST capacitor, and d is the thickness of the BST.

Fig. 2 shows a typical plot for the relative dielectric constant as a function of the applied dc voltage across the parallel-plate BST capacitor between 45 and 500 MHz. Approximate tunabilities of 71% (3.4 : 1) at 9 V were obtained. The loss tangent values were typically in the range 0.003–0.009 over this frequency range.

The device quality factor (Q_{total}) of the measured BST capacitors was extracted from the measured data using the following relation

$$Q_{total} = \frac{imag(Z)}{real(Z)} \quad (3)$$

where Z is the impedance measured by the network analyzer. The device Q includes losses due to the BST ($Q_{\rm BST}$) and the conductor losses ($Q_{conductor}$) which are related by

$$\frac{1}{Q_{total}} = \frac{1}{Q_{\rm BST}} + \frac{1}{Q_{conductor}} \quad (4)$$

where $Q_{\rm BST}$ and $Q_{conductor}$ are obtained from

$$Q_{\rm BST} = \omega R_P C = \frac{1}{\tan\delta} \quad (5)$$

$$Q_{conductor} = \frac{1}{\omega R_S C}. \quad (6)$$

Using (4)–(6), the quality factors due to the BST and the conductor losses were extracted from the total quality factor, respectively. Fig. 3 shows the measured and modeled device Q vs. frequency plot as well as the extracted Q factors due to the BST and the conductor losses for a typical BST capacitor measured in this work with $C = 65$ pF at 0 V dc bias. This device quality factor is comparable with the Q factors for commercially available semiconductor based varactor diodes with similar capacitance (typical 65 pF commercial varactor diodes have Q factors in the range 40–80 at 50 MHz).

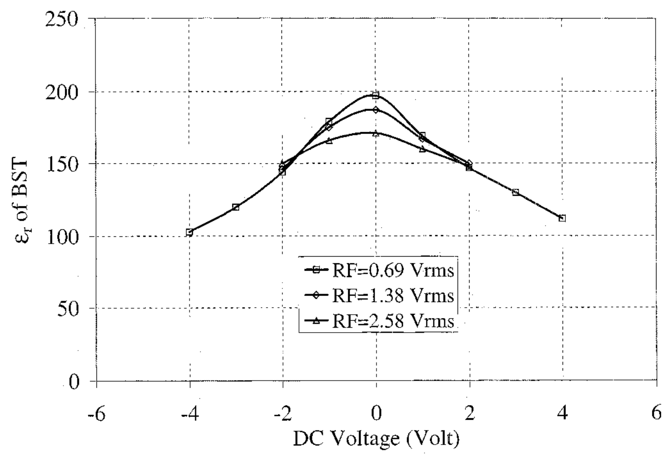

Fig. 4. Relative permittivity of BST for high RF voltages ($f = 50$ MHz, thickness = 700 Å).

It can be concluded from Fig. 3 that at lower frequencies, both $Q_{\rm BST}$ and $Q_{conductor}$ contribute to the device Q (Q_{total}), whereas as the frequency is increased, Q_{total} is dominated by $Q_{conductor}$, which is inversely proportional to the frequency. It can be clearly seen from Fig. 3 that the dielectric losses of the BST itself ($\tan\delta = Q_{\rm BST}^{-1} = 0.008$) has little impact on Q_{total} at frequencies above 300 MHz. Conversely, it can be stated that at higher frequencies, a substantial improvement in device quality factor can be expected if the conductor losses are reduced. One straightforward solution is to increase the capacitor electrode thickness or to use a metallization with a higher conductivity.

Large signal characterization of the BST capacitors is also performed to better understand the effect of large RF signal amplitudes on the tunability of BST capacitors. Fig. 4 shows the plots of the relative permittivity as a function of the applied dc voltage for various RF signal amplitudes. The breakdown voltage of 8 V for this particular sample limited the application of higher dc voltages, while high RF voltage levels were

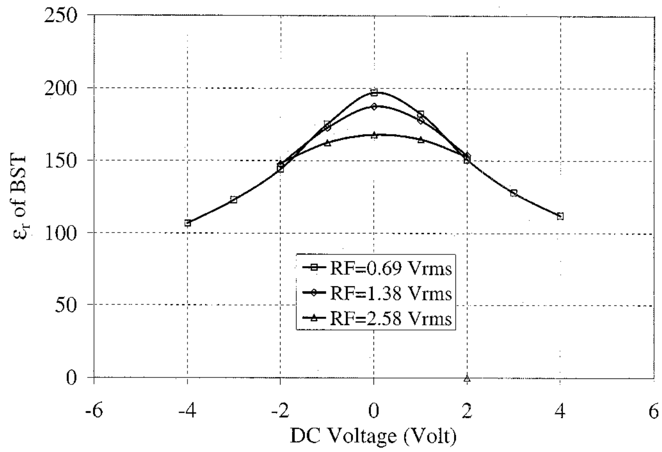

Fig. 5. Simulation results for the tunability degradation of the BST capacitors ($f = 50$ MHz, thickness = 700 Å).

applied. It can be seen that the capacitance tunability decreases with increasing the signal amplitude. To model this behavior, a 5th order polynomial was fitted to the dc C–V curve for this capacitor. The polynomial was then used to define a nonlinear capacitance in Agilent-ADS software. Almost the same tunability variation versus the applied RF voltage is observed with the harmonic balance simulation results shown in Fig. 5. The simulation results indicate that the drop in tunability is proportional to the rms value of the applied RF voltage, and the dc C–V curve is sufficient for predicting this behavior at RF frequencies. It should be mentioned that tunability and power handling capability of varactor diodes degrade dramatically due to the application of high RF voltages. This is because for proper operation, varactor diodes must be reverse biased by at least the peak value of the RF voltage amplitude. On the other hand, this requirement is not present in BST based capacitors, making them attractive for the design of high power and tunable RF and microwave circuits.

III. Conclusion

Measurement results for parallel plate capacitors fabricated on MOCVD grown thin film BST with an approximate tuning range of 71% (3.4 : 1) at 9 V were presented. The typical dielectric loss tangents were in the range 0.003–0.009 at VHF. The device quality factor for the BST capacitors was separated into components due to the BST loss and those due to the conductor losses. It was determined that the measured device Q for BST varactors is comparable with the device Q for commercially available varactor diodes of similar capacitance. Furthermore, the effect of large RF signal amplitudes on the capacitance tunability was investigated.

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