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Barium strontium titanate thin film varactors on r-plane sapphire

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***Abstract* — This paper presents the microwave properties of barium strontium titanate (BST) thin films on r-plane sapphire substrates. A series of films with thickness 25 – 400 nm was prepared by pulsed laser deposition (PLD). Microwave properties of the films, including capacitance tunability and loss tangent, were extracted by patterning interdigitated capacitors (IDCs) on the film surface. The highest tunability of 64% was observed in the 200 nm film. These results demonstrate the possibility of integrating BST into the silicon on sapphire process.**

***Index Terms* — Ferroelectric thin films, silicon on sapphire, microwave varactors.**

I. Introduction

Barium strontium titanate (BST) thin films are currently being studied for applications such as high density dynamic random access memories (DRAMS) [1], small footprint DC blocking capacitors [2] and tunable microwave circuits, such as phase shifters [3] and bandpass filters [4]. An important step towards the commercialization of BST-based devices is the integration of BST films with semiconductors. Despite the large volume of research, there has been limited progress towards the integration of BST with semiconductor technology.

One of the difficulties associated with BST thin film deposition is the high substrate temperature, typically 450 – 700°C [5] required to form the tunable perovskite phase of the material. The design of a low loss bottom electrode on silicon which is stable at high deposition temperatures is not straightforward. Several layers are generally required, for example $Pt/Au/Pt/TiO_2/SiO_2/Si$ [6]. Problems with hillock formation in the Pt layer have been reported [7], due to the difference in thermal coefficients between the Pt and Si layers. Improved bottom electrodes have been achieved using c-plane sapphire, [8] however this substrate material is not compatible with silicon-based processes.

Silicon on sapphire (SoS) technology offers a potential solution to the problem of BST integration. The SoS process uses r-plane sapphire as the substrate material [9]. In recent work [10], BST was deposited on a SoS wafer, and the underlying Si layer was subsequently converted to SiO_2 by annealing in oxygen for 48 hours at 1000ºC. Since no Si remains after annealing, BST-based devices and semiconductors cannot be fabricated on the same chip using this process.

In this paper, the microwave properties of BST thin films deposited directly on r-plane sapphire are studied. Several different film thicknesses, in the range of 25 – 400 nm were investigated, so as to map out the relationship between the film thickness and microwave properties of varactors formed from these films. Interdigitated varactors were formed by electroplating a seed pattern on the surface of the BST film, as described below.

II. BST Thin Film Deposition and Varactor Fabrication

Pulsed laser deposition (PLD) was used to deposit the BST material on 10 x 10 x 0.5 mm sapphire substrates (Techno Chemics, Inc.) The PLD system employed a KrF excimer laser (λ = 248 nm) with 2 Hz repetition rate focused to 2 $J{\cdot}cm^{-2}$ energy density. Prior to deposition, the substrates were annealed inside the deposition system at 600°C in 100 mTorr of flowing oxygen, in order to remove any residual surface contamination.

A series of depositions were performed from a stoichiometric $Ba_{0.6}Sr_{0.4}TiO_3$ circular target, for BST films thickness of 25, 50, 100, 200 and 400 nm. The substrate temperature was maintained at 700ºC for all depositions. After deposition, ~1 Atm of oxygen was admitted to the deposition chamber, and the films were *in-situ* annealed at 700ºC for 6 hours before cooling to room temperature.

Thick interdigitated capacitor (IDC) structures were formed on the surface of the BST film by electroplating. Seed metal layers of Ti, Ni and Au were successively deposited by e-beam evaporation and patterned by lift-off. Interdigitated Au electrode structures were electroplated to a thickness of ~2.5 μm, after which the seed layer was removed by wet etching. The finger length of the varactors ranged from 80 – 120 μm and the gap between the fingers was 2 – 8 μm, while the finger width was fixed at 5 μm. Each varactor consisted of two sets of interdigitated electrodes (8 fingers each), and was designed for probing in the ground-signal-ground (GSG) configuration. Open and short circuit calibration standards were also patterned next to each varactor, as shown in Fig. 1.

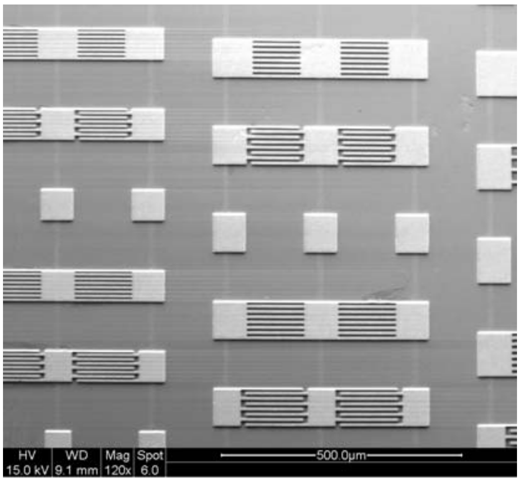

Fig. 1. Array of interdigitated capacitors (IDCs) with adjacent open and short circuit calibration standards.

III. Device Characterisation

X-ray diffraction (XRD) measurements showed that all of the films were polycrystalline and single phase. A detailed description of the material results and their relation to the microwave properties of the devices will be reported elsewhere [11]. The method and results of the microwave characterization procedure are given below.

A. On-wafer calibration

Open-circuit and short circuit calibration standards, with the same finger / pad dimensions as the varactors, were patterned next to each varactor device on the BST film. This allowed the extraction of the parasitic inductance, capacitance and resistance associated with the electrode metallization, following the procedure given in [5, 12]. A schematic of the BST varactor with associated parasitic elements is given in Fig. 2.

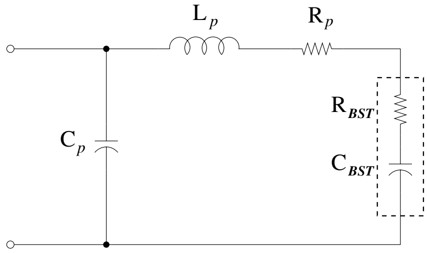

Fig. 2. Equivalent circuit of BST varactor, incorporating pad parasitics L_p, C_p and R_p, based on [5].

One port reflection (S_{11}) measurements of the open circuit were used to calculate C_p. Values for L_p and R_p were then extracted by measuring the short circuit standard. The Q-factor of the devices was calculated using

$$Q = \frac{1}{\omega R_{BST} C_{BST}} . \qquad (1)$$

A Matlab optimisation routine was used to calculate the frequency dependent values of the circuit elements in Fig. 2.

B. Measured Results

Microwave characterization of the BST varactors was performed on an Anritsu 37369A vector network analyzer (VNA). The VNA was connected to a wafer probe station equipped with 200 μm pitch GSG wafer probes. The bias voltage for the varactors was supplied via the internal bias tee of the VNA, and was therefore limited to ±40 V.

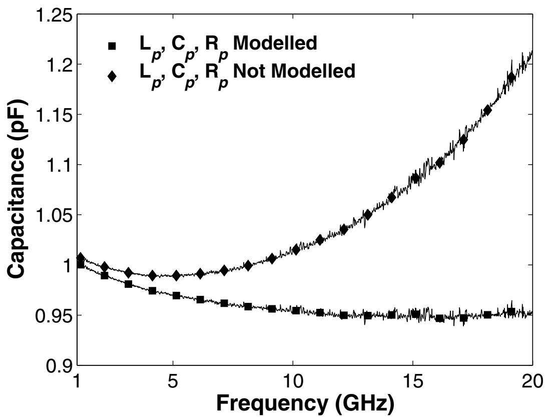

Fig. 3. Extracted BST varactor capacitance (C_{BST}) with and without modeling the pad parasitics L_p, C_p and R_p.

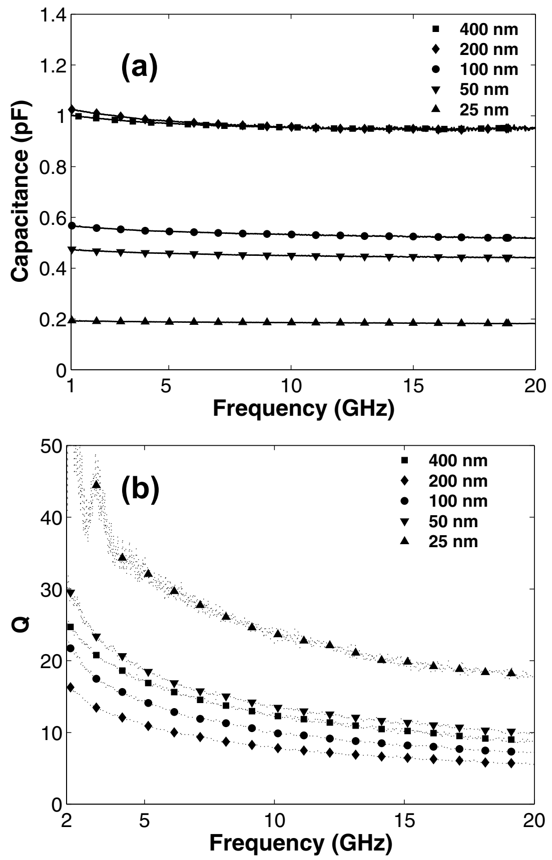

Fig. 4. Measured zero bias performance of BST varactors as a function of film thickness at (a) capacitance C_{BST}, and (b) Q-factor.

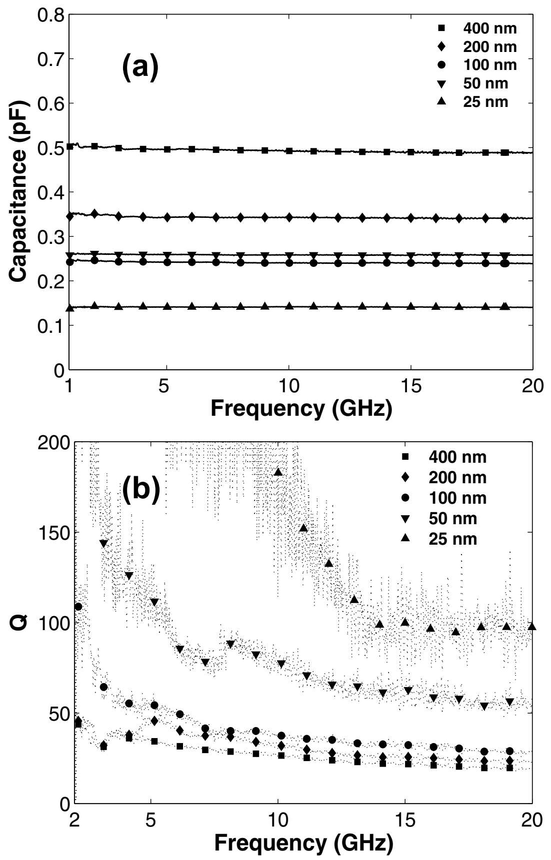

Fig. 5. Measured 40 V bias performance of BST varactors as a function of film thickness: (a) capacitance C_{BST}, and (b) Q-factor.

For each device, three measurements were performed (open circuit, short circuit and varactor). Typical values for C_p and L_p were 6 fF and 10 pH, respectively. The effect of not modeling the pad parasitics is shown in Fig. 3. Failing to model the parasitics causes a large variation in the extracted capacitance C_{BST} in wide band measurements. Since the calculations for tunability and dielectric constant are generally based on the value of C_{BST}, it is important to account for the pad parasitics.

Zero-bias measurements for a series of varactors with different BST film thickness are shown in Fig. 4. Figure 5 shows measured results for the same devices at 40 V bias. The data provided is for 2 μm gap devices with the highest capacitance tunability for a given film thickness. Note that the capacitance tunability is calculated using

$$Tun = \frac{C(0V) - C(40V)}{C(0V)} \times 100\,\%\,. \qquad (2)$$

Values for the device tunability at each film thickness are given in Table 1. Note that the lowest tunability 2 μm gap devices on each film had a capacitance variation ~5% lower than that of the highest tunability devices. Devices with larger gaps between the electrodes showed lower tunability, due to the lower bias field across the BST film. The Q-factor is shown only above 2 GHz due to large fluctuations in the extracted resistance R_{BST} at lower frequencies.

C. Discussion

A high tunability of 64% or 2.8:1 was measured for the 200 nm film, at a bias field of 200 $kV \cdot cm^{-1}$. However, this device had the lowest Q-factor of ~7.8 at 10 GHz. Devices with lower tunability had a higher Q-factor, with the best Q-factor observed in the 25 nm film. Interestingly, the 400 nm film showed a lower tunability than the 200 nm film. In epitaxial BST films, the highest tunability is

TABLE I
SUMMARY OF ELECTRICAL RESULTS

	Capacitance			Q-Factor (1/tanδ) (10 GHz)	
Film Thickness [nm]	C(0 V) [pF]	C(40 V) [pF]	*Tun [%]*	Q(0 V)	Q(40 V)
25	0.19	0.14	24	22.9	180
50	0.45	0.26	43	13.4	78.3
100	0.53	0.24	55	9.90	37.8
200	0.96	0.34	64	7.80	32.2
400	0.99	0.49	50	11.8	26.9

generally observed in thicker films due to strain relaxation [13]. However, it appears that this is not the case in polycrystalline BST films on r-plane sapphire.

These results compare favourably with other reports of interdigitated BST varactors [14]. Importantly, the process temperature does not exceed 700°C. Depending on proprietary details of the SoS process, this may allow BST to be incorporated in the SoS-based circuits.

VI. CONCLUSION

A series of BST films with thickness in the range of 25 – 400 nm was deposited by PLD. Thick gold IDCs were patterned on the BST films by electroplating, and the microwave properties of the devices were measured from 1 – 20 GHz. The best tunability of 64% was observed in a varactor on the 200nm film. Since the processing temperatures are below 700°C, BST films grown on r-plane sapphire are potential candidates for integration with SoS technology.

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