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Low frequency and microwave performances of $Ba_{0.6}Sr_{0.4}TiO_3$ films on atomic layer deposited TiO_2/high resistivity Si substrates

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Abstract We report on high tunablity of $Ba_{0.6}Sr_{0.4}TiO_3$ (BST) thin films realized through the use of atomic layer deposited TiO_2 films as a microwave buffer layer between BST and a high resistivity (HR) Si substrate. Coplanar waveguide (CPW) meander-line phase shifters using BST/TiO_2/HR-Si and BST/MgO structures exhibited a differential phase shift of 95° and 24.4°, respectively, at 15 GHz under an electric field of 10 kV/cm. The figure of merit of the phase shifters at 15 GHz was 30.6°/dB for BST film grown on a TiO_2/HR-Si substrate and 12.2°/dB for BST film grown on a MgO single crystal substrate. These results constitute significant progress in integrating BST films with conventional silicon technology.

Keywords BST · Buffer layer · Coplanar waveguide · Phase shifter

1 Introduction

Microwave tunable circuits, including filters, matching networks, and phase shifters offer the flexibility to adapt to changes in operating conditions, such as frequency, impedance environment or RF drive level, a property that is highly sought after in the wireless communications industry [1–3].

$Ba_xSr_{1-x}TiO_3$ (BST) has been widely studied as a ferroelectric material for microwave device circuits, primarily due to the highly nonlinear dependence of the dielectric constant by electric field in the vicinity of room temperature [4]. For application of tunable devices, it is desirable to have a maximal dielectric constant change ratio [dielectric tunability $= (\varepsilon_{\max} - \varepsilon_{\min})/\varepsilon_{\max}$] and minimal dielectric loss. Many studies have focused on increasing the dielectric tunability and reducing the loss of epitaxial BST films grown on single crystal substrates such as MgO and $LaAlO_3$ [5–6]. However, the real emergence of BST films into future technologies will to a large degree depend on the ease and effectiveness with which they can be integrated with the conventional Si substrates [7]. In a previous work focusing on the low frequency dielectric properties of BST film grown on a Si substrate with a TiO_2 buffer layer, we demonstrated that TiO_2 buffer layers significantly increased the dielectric tunability of BST films and minimized power loss via the Si substrate [8]. In the present study, we report on high dielectric tunability and improved microwave loss characteristics of BST films on high resistivity Si realized through the insertion of an ALD-grown TiO_2 buffer layer. The performance of a coplanar waveguide (CPW) BST/TiO_2/HR-Si phase shifter was investigated and compared with that of a BST/MgO phase shifter.

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2 Experimental

The process conditions for TiO_2 film growth were described in detail in a previous paper [8]. TiO_2 buffer layers were grown by ALD onto high resistivity (HR) Si (2 kΩcm) substrates followed by Pulsed Laser Deposition (PLD) of BST thin films onto a TiO_2 buffer layer. The substrate temperature and oxygen ambient pressure during PLD were 750°C and 50 mTorr, respectively. Laser ablation was carried out at a laser fluence of 1.5 J/cm^2 and a repetition rate of 5 Hz using a KrF excimer laser source ($\lambda = 248$ nm). The nonlinear dielectric properties of the BST/TiO_2/Si thin films were measured using an interdigital capacitor (IDC) structure. The IDC, with a total of 10 fingers, an overlap length of 1000 μm, and a finger gap of 10 μm was fabricated on BST/TiO_2/Si utilizing standard photolithographic and lift-off processes. The CPW phase shifter circuits were fabricated on the BST film (0.5 μm thick, deposited on TiO_2/HR-Si substrate). The length of the meander line was chosen to be 24 mm. A CPW meander line with a 170 μm centerline and a 50 μm gap was used. In order to obtain lager phase shifts, narrow transverse slits were inserted into the center signal line [9]. 1.5 μm thick Au/Cu/Ti metal layers were deposited via dc magnetron sputtering in order to produce the IDC and CPW electrodes. Microwave property measurements were conducted on an HP 8510C vector network analyzer using S parameter measurement in a frequency range of 0.5 to 20 GHz at room temperature.

3 Results and discussion

The nonlinear dielectric properties of BST films were investigated through an assessment of interdigital capacitors fabricated on BST/TiO_2/Si and BST/MgO. The capacitance tunability is defined as [(C(0)-C(V))/C(0)] × 100, where C(0) and C(V) are the capacitances at zero and high voltage, respectively. As shown in Fig. 1, the BST film grown on a TiO_2/HR-Si substrate at 2 GHz showed a capacitance tunability of 33.2% under an applied voltage of 40 V. This value is larger than that of BST epitaxially grown on a MgO single crystal substrate (tunability 21%, at 40 V). Table 1 shows the dielectric properties of BST films at 2 GHz grown on HR-Si, TiO_2/HR-Si, and MgO substrates, respectively. As anticipated, epitaxially grown BST film on a MgO substrate exhibited a larger Q (19.93) than that (12.61) of BST film grown on a TiO_2/HR-Si substrate.

Table 1 Dielectric properties at 2 GHz of BST thin films grown on HR-Si, TiO_2/HR-Si, and MgO substrates, respectively

	Q factor (1/tan δ) at 0 V	Tunability(%) at 40 V	FOM
BST/HR-Si	8.48	12.5	106
BST/TiO_2/HR-Si	12.61	33.2	418.7
BST/MgO	19.93	21	418.5

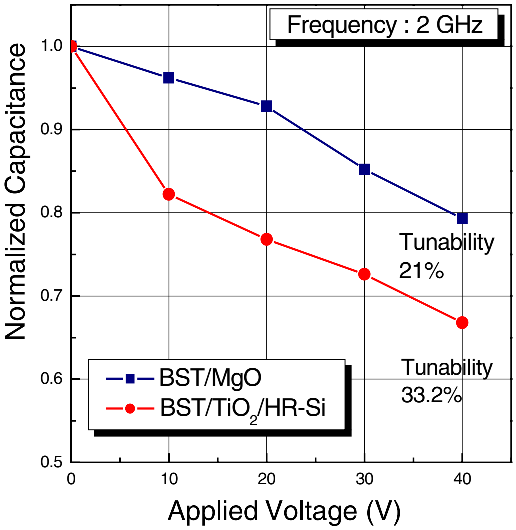

Fig. 1 Normalized capacitance-voltage characteristics of BST thin films grown on MgO and TiO_2/HR-Si (2 kΩcm) at a frequency of 2 GHz

The figure of merit (FOM), product of capacitance tunability, and quality factor Q determine the utility of tunable ferroelectric films in terms of device applications. The FOM value (418.7) of BST film grown on a TiO_2/HR-Si substrate is compatible with that (418.5) of BST film on a MgO single crystal substrate. In order to demonstrate the advantages of a TiO_2 buffered high resistivity Si substrate for application in microwave frequencies, a phase shifter with a coplanar waveguide (CPW) meander line structure was fabricated on a BST/TiO_2/HR-Si structure.

Figure 2 shows the measured microwave properties of the CPW meander line phase shifter based on BST/TiO_2/HR-Si. Figure 2 (a) shows the differential phase shift (with respect to the insertion phase at zero bias) of the phase shifter as a function of frequency measured at different dc biases of 0, 10, 20, 30, 40, and 50 V. As the frequency increased, the differential phase shift linearly increased. A phase shift of 95° was obtained at 15 GHz with a dc bias of 0–50 V. This corresponds to a phase shift per applied voltage of 1.9°/V. Figure 2 (b) shows the insertion loss (S_{21}) as a function of frequency and applied bias voltages. The insertion loss increased with increasing frequency and improved with bias voltage, a typical trend for ferroelectric CPW phase shifters. The measured insertion loss at 15 GHz ranged from 3.1 to 1.2 dB with an applied voltage of 0 and 50 V, respectively. Figure 3 shows the measured microwave properties of the CPW meander-line phase shifter based on BST/MgO. Figures 3 (a) and 3 (b) show the differential phase shift as well as the insertion loss of the phase shifter as a function of frequency measured at different dc biases of 0, 10, 20, 30, 40, and 50 V. The differential phase shift was 24.4° at 15 GHz

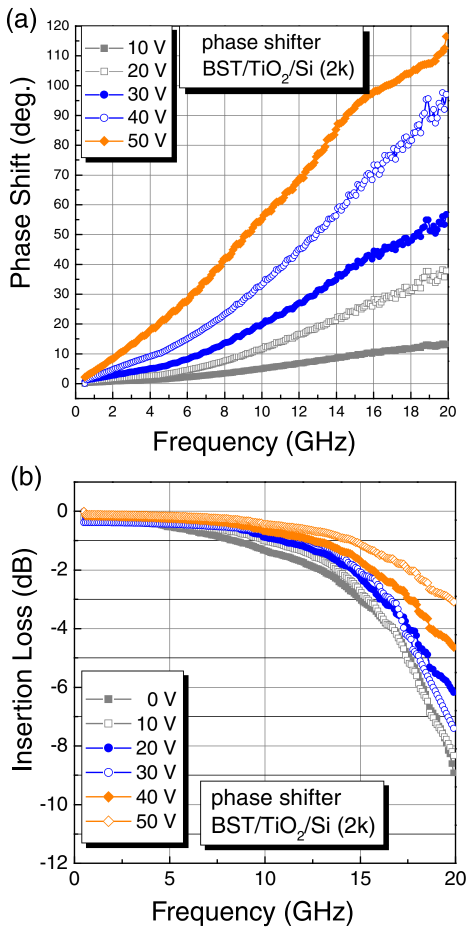

Fig. 2 Measured microwave properties of a CPW phase shifter based on BST/TiO_2/HR-Si. (a) differential phase shift and (b) insertion loss

with a dc bias of 0–50 V. This phase shift amounts to only 0.49°/V. The insertion loss measured at 15 GHz ranged from 2.0 to 0.4 dB with a dic bias of 0–50 V, respectively. Figure 4 shows the differential phase shift for the CPW phase shifter based on BST/TiO_2/HR-Si and BST/MgO structures as a function of applied dc bias voltages up to 50 V at 15 GHz. The measured differential phase shifts were 95° and 24.4° for BST/TiO_2/HR-Si and BST/MgO, respectively. As shown in Fig. 4, since the differential phase shift for BST/TiO_2/HR-Si was not fully saturated up to 50 V, larger phase shift for BST/TiO_2/HR-Si can be obtained with a higher dc bias voltage. In contrast, at 50 V, the phase shift for BST/MgO was only 24.4°, markedly less than that for BST/TiO_2/HR-Si. These results are significant because a large differential phase shift of 95° was achieved for the CPW meander line phase shifter with a large signal to ground gap of 50 μm at a low voltage of 50 V. The figure of merit of a phase shifter is defined by the differential phase shift divided by the maximum insertion loss for zero voltage. At a measured frequency of 15 GHz, the phase shifter fabricated on BST film grown on a TiO_2/Si substrate showed a larger figure of merit (FOM) of 30.6°/dB as a result of improved phase tuning while retaining an appropriate insertion loss. In comparison, a FOM of only 12.2°/dB was obtained for the BST/MgO structure.

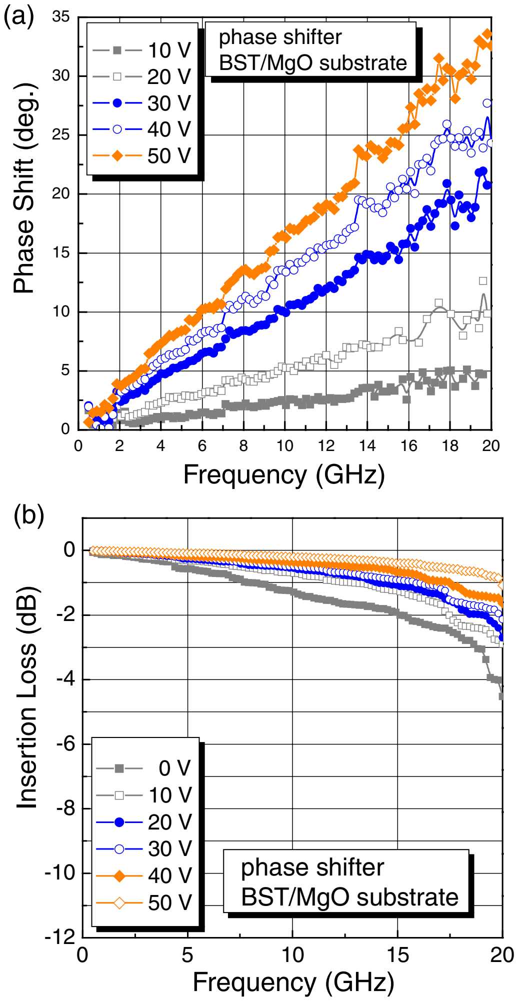

Fig. 3 Measured microwave properties of a CPW phase shifter based on BST/MgO. (a) differential phase shift and (b) insertion loss

The overall effective dielectric constant of the BST/substrate was determined from microwave measurement of the end-gap line resonator with a CPW structure. The resonator was fed by a capacitive coupling gap of 10 μm. The width of the signal conductor and the spacing between the signal conductor and the ground plane was taken to be 170 μm and 50 μm, respectively. The DC bias dependent frequency response of the resonator based on BST/TiO_2/HR-Si is shown in Fig. 5 (a). The resonant frequencies were 12.887 GHz, 13.14 GHz, and 13.307 GHz with a bias of 0, 30, and 50 V, respectively. The frequency tuning range was 420 MHz at an applied voltage of 50 V. As the DC bias voltage was increased, the resonance frequency also increased due to the decrease in the dielectric constant of BST. In order to measure the effective dielectric constant, the equation below was used. The effective dielectric

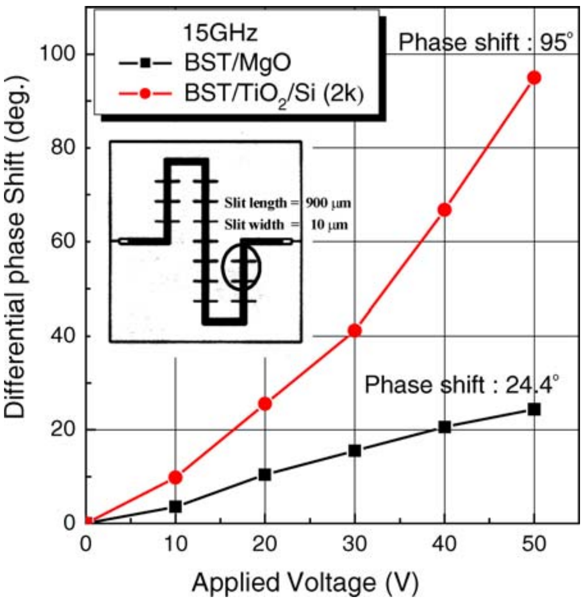

Fig. 4 Differential phase shift as a function of dc bias voltage for BST/MgO and BST/TiO_2/HR-Si structures at 15 GHz. Inset shows a schematic layout of the CPW phase shifter

constant is a function of length and resonance frequency [9].

$$\sqrt{\varepsilon_{\text{eff}}} = \frac{c}{2 \cdot l \cdot f} \tag{1}$$

where c and l indicate the speed of light and the length of the resonator, respectively. The corresponding effective dielectric constants for the resonator with a center frequency of 12.887 GHz and 13.307 GHz were 10.45 and 9.80, respectively. On the other hand, the DC bias dependent frequency response of the resonator fabricated on BST/MgO, as shown in Fig. 5 (b), was 14.695 GHz, 14.845 GHz, and 14.9 GHz with a bias of 0, 30, and 50 V, respectively. The corresponding effective dielectric constants for the resonator with a center frequency of 14.695 GHz and 14.9 GHz were 9.01 and 8.77, respectively. At an applied voltage of 50 V, the frequency tuning range of the resonator using BST/MgO was only 205 MHz, significantly less than that (i.e. 420 MHz) of BST/TiO_2/HR-Si (2 kΩcm). The relative dielectric constant of BST was obtained from the measured effective dielectric constant using a well known conformal mapping-based model for multi-layer substrates [10–11]. The resulting dielectric constants are shown in Table 2. The relative dielectric constants of BST grown on a TiO_2/HR-Si substrate were obtained around 419 at 0 V and 300 at 50 V. This corresponds to a dielectric tunability of 28.4% with 10 kV/cm, much larger than that (i.e. 6.4%) of BST grown on MgO substrate. Even though the relative dielectric constants of BST (690 at 0 V) epitaxially grown on MgO were much larger than that of BST (419 at 0 V) grown on TiO_2/HR-Si, the thickness of the BST layer is only 0.1% of the total BST/substrates thickness. Therefore, the effect of the substrate, which accounts for 99.9% of the total thickness, is significantly larger in the overall effective dielectric constant of the BST/substrate.

Table 2 Summary of dielectric properties from the CPW resonators

	BST/TiO_2/HR-Si		BST/MgO	
	ε_{eff}	ε_{BST}	ε_{eff}	ε_{BST}
0 V	10.45	419	9.01	690
50 V	9.80	300	8.77	646
Tuning	6.2%	28.4%	2.7%	6.4%

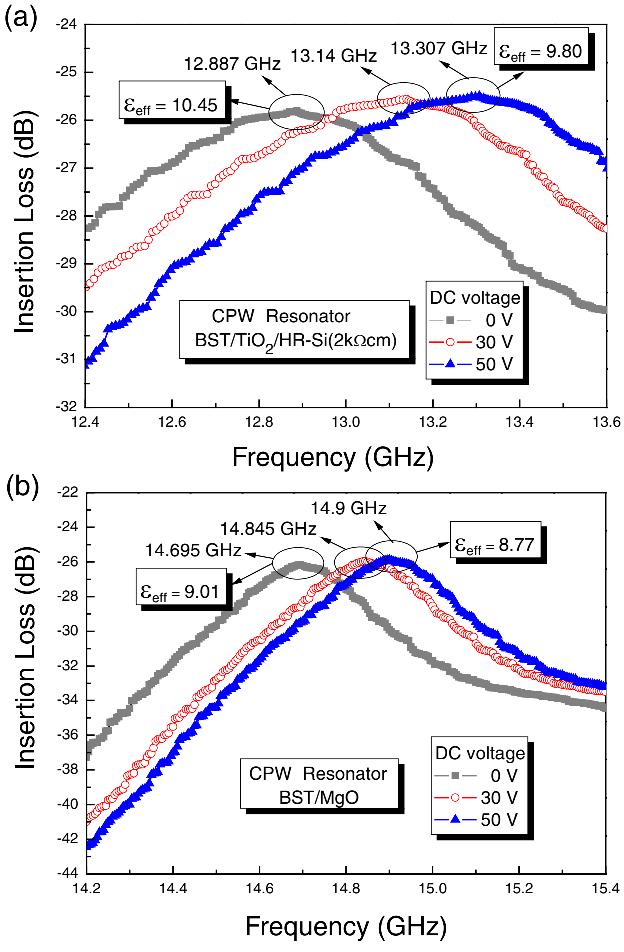

Fig. 5 DC bias dependent frequency response of CPW resonator based on (a) BST/TiO_2/HR-Si and (b) BST/MgO

A relative dielectric constant of ~15.5, at a bias voltage range of 0–50 V, was obtained for TiO_2 buffered HR-Si. This value is larger than, the theoretical dielectric constant (9.6) of the MgO substrate. Improved dielectric tunability, and thus higher frequency tuning agility, can be realized by incorporating a high-K TiO_2 buffer layer. This layer increases the overall effective dielectric constant, thereby minimizing the electric field attenuation in coplanar designs such as IDC and CPW phase shifters.

4 Conclusions

TiO_2 films were grown on high resistivity Si substrates by atomic layer deposition as buffer layers for the Si integration of BST films. BST films grown on TiO_2/HR-Si substrates showed larger phase shifting capability than BST films grown on MgO substrates. The figure of merit of phase shifters at 15 GHz was 30.6°/dB for BST grown on a TiO_2/HR-Si substrate and 12.2°/dB for BST grown on a MgO single crystal substrate. This indicates that utilization of the BST/TiO_2/HR-Si structure is a promising route for the development of Si integrated microwave tunable devices such as phase shifters and band-pass filters.

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