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Microwave performance of thin film ferroelectric varactors in the wide temperature range of −223 °C to +227 °C

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Abstract

Parallel-plate Au(Pt)/$Ba_{0.25}Sr_{0.75}TiO_3$/(Pt)Au thin film varactors are fabricated on high resistive Si substrate and characterized at 1 MHz and microwave frequencies up to 45 GHz in the temperature range of −223 °C to +227 °C. The relative tunability of capacitance decreases with temperature, as capacitance does, from 80 to 90% at −193 °C down to 10% at +227 °C. The temperature coefficient of capacitance in the temperature range −55 to +125 °C is approximately 0.3% at 20 GHz and zero dc field. The temperature dependence of the varactor loss tangent, in general, follows that of the capacitance. The loss tangent at zero dc field and 20 GHz is less than 0.1 at −193 °C and less than 0.02 at +227 °C. The figure of merit of the varactor, taking into account both the tunability and the loss tangent, at 20 GHz is more than 1000 at −193°C and 50 at +227 °C.

Keywords: $BaTiO_3$ and titanates; Films; Capacitors; Microwave; Dielectric properties

1. Introduction

Recently voltage tunable capacitors (varactors) incorporating $Ba_{0.25}Sr_{0.75}TiO_3$ (BST) ferroelectric films with performances comparable or better than semiconductor analogues have been developed and successfully used in commercially competitive microwave circuits.[1–3] The use of highly conductive metal bottom electrodes made of thick Pt (up to 2 μm), Au, and Cu[1,4–6] allows a significant reduction of the loss associated with the series resistance in the electrodes. In some cases, the *Q*-factor of the varactors is limited mainly by the extrinsic loss in the ferroelectric film.[7] These are the losses observed in ferroelectric varactors with high temperature superconductor (HTS) electrodes,[8] where the losses in the plates may be neglected. The utilization of normal metal electrodes, instead of HTS electrodes, opens possibilities for applications of the ferroelectric varactors in commercial microwave systems in a wider temperature range. Cost, size, and weight savings can be achieved by replacing traditional centralized microwave systems with more distributed architectures, including remotely-placed units. In some cases, this may require operation of the electronics at extremely low or high temperatures. The investigation of the microwave performance of the ferroelectric varactors in a wide temperature range will show their potential for applications in systems designed for operation at extreme temperatures. Very little is published about experimental microwave performance (capacitance, tunability and loss tangent) of ferroelectric varactors in a wide temperature range. In this work, we present the parameters of the high *Q*-factor BST thin film varactors (capacitance, tunability and loss tangent) measured at 1 MHz and frequencies up to 45 GHz in the temperature range of −223 °C to +227 °C.

2. Experimental procedure

Platinized silicon (Pt/TiO_2/SiO_2/Si) with resistivity $\rho_{Si} = 5\,k\Omega\,cm$ is used as the substrate. Pt (50 nm)/Au (0.5 μm) bottom electrode films are deposited by e-beam evaporation at room temperature, followed by growth of 560 nm thick BST films using a KrF excimer laser ($\lambda = 248$ nm, $\tau = 30$ ns) operating at 10 Hz with an energy density of 1.5 J cm^{-2} to ablate the $Ba_{0.25}Sr_{0.75}TiO_x$ target. The substrate temperature is maintained at 650 °C and the oxygen pressure at 40 Pa. After deposition the samples are cooled down to room temperature at 77 kPa oxygen pressure. To keep the parallel-plate structure symmetric, Au (0.5 μm)/Pt (50 nm) top electrodes are deposited on the BST film by e-beam evaporation at room temperature. A lift-off process is used to pattern the top electrodes. The

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top electrode consists of a central circular patch surrounded by a co-centric top ground plane. The latter is capacitively coupled ("connected") to the bottom plate (ground plane). Test structures with radii of the center patches $r_c = 5$ and 15 μm are used in the experiments. The capacitance–voltage dependences of the varactors with $r_c = 15$ μm are measured in the temperature range of −223 °C to +227 °C using a HP 4285A LCR-meter at 1 MHz and at 1.0 V_{rms} rf voltage. Voltages as high as 20 V are applied, corresponding to a field up to 360 kV/cm. The microwave parameters of the varactors with $r_c = 5$ μm are measured in the temperature range of −193 °C to +227 °C using a HP 8510C vector network analyzer and Ground-Signal-Ground microprobes in the frequency range 100 MHz to 45 GHz. Two separate calibrations in this frequency range, below and above 10 GHz, are used to increase the number of experimental points. The complex input impedance of the varactors is extracted from one port reflection measurements. The capacitance C and the loss tangent tan δ are computed from the complex impedance $Z = R + jX$, $C = -1/\omega X$, $\tan\delta = -R/X$.

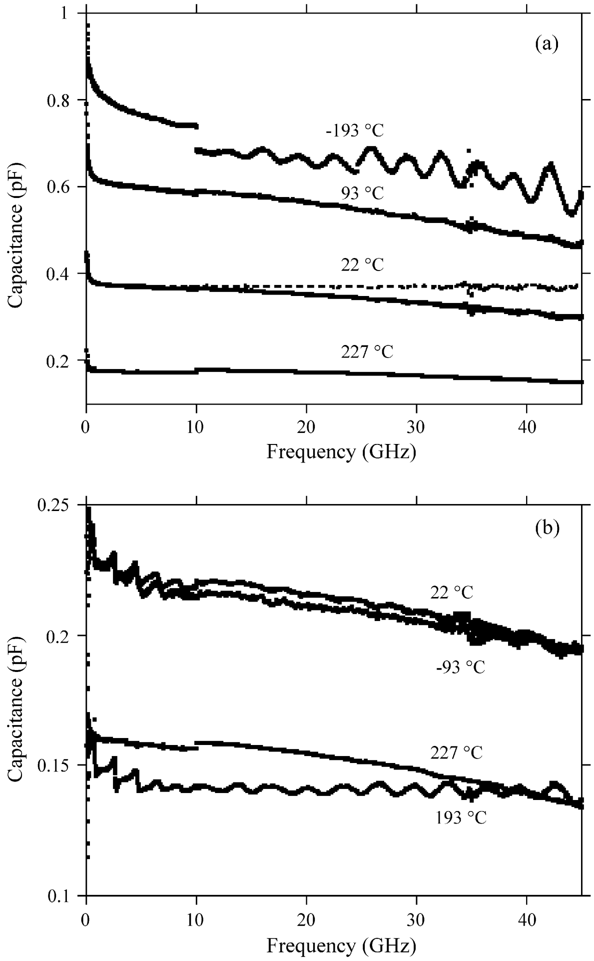

Fig. 2. Capacitance of a BST varactor vs. frequency at different temperatures without (a) and under 20 V dc bias (b). The dotted line represents the room temperature capacitance calculated subtracting a inductive portion ($L_{ser} = -8$ pH) from the imaginary part of the impedance, $C = -1/\omega(X - \omega L_{ser})$.

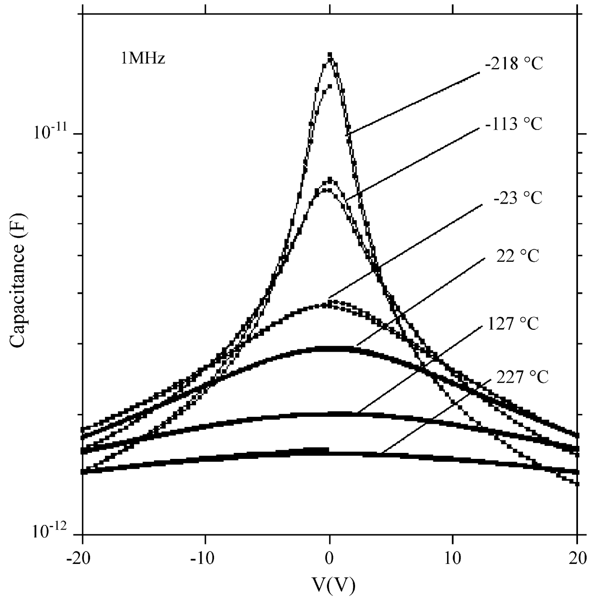

Fig. 1. Capacitance of a BST varactor vs. dc voltage measured at 1 MHz and different temperatures.

3. Results and discussions

Fig. 1 shows typical dc voltage dependences of the varactor capacitance measured at 1.0 MHz and different temperatures. The capacitance and the relative tunability of the varactor at 20 V (360 kV/cm field) increases as the temperature decreases. Fig. 2a shows some of the capacitance–frequency dependences of a BST varactor measured at different temperatures without dc bias. At lower temperatures, the dispersion of capacitance below 10 GHz may be associated with relaxation of polarization of local polar regions and/or ferroelectric domains. The frequency dispersion above 10 GHz is due to the negative series inductance L_{ser} included in a commercial calibration software used in our measurements. The dotted line in Fig. 2a represents the room temperature capacitance calculated using the imaginary part of the impedance, and taking into account the negative inductance ($L_{ser} = -8$ pH): $C = -1/\omega(X - \omega L_{ser})$. In this case, the room temperature capacitance is relatively frequency independent in the whole frequency range indicating that polarization is mainly due to the soft-mode phonon contribution with a resonant frequency of about 1.2 THz.[9,10] Fig. 2b shows the capacitance–frequency dependences of a BST varactor at the same temperatures as in Fig. 2a but under 20 V dc bias. The resonant inflexions of capacitance in the frequency range 1–10 GHz are caused by the resonant conversion of the microwave power into acoustic waves associated with electrostriction and field induced piezoelectric effects.[11] It can be seen that these effects become negligible at higher temperatures. At 20 GHz, without dc bias, the temperature coefficient of capacitance, TCC, in the temperature range $\Delta T = -55$ to 125 °C is: $\mathrm{TCC} = \Delta C/(C(RT)\Delta T) \approx 0.3\%$, where ΔC is the change in capacitance and $C(RT)$ is the capacitance at 25 °C. In the whole frequency range the tunability, $n_r = (C(0) - C(V))/C(0)$, as the 0 V capacitance (Fig. 1), decreases monotonously with temperature from 80 to 90% at −193 °C down to 10% at +227 °C. The tunability at −193 °C and 1 MHz (90%) is higher than that at 20 GHz (80%) due

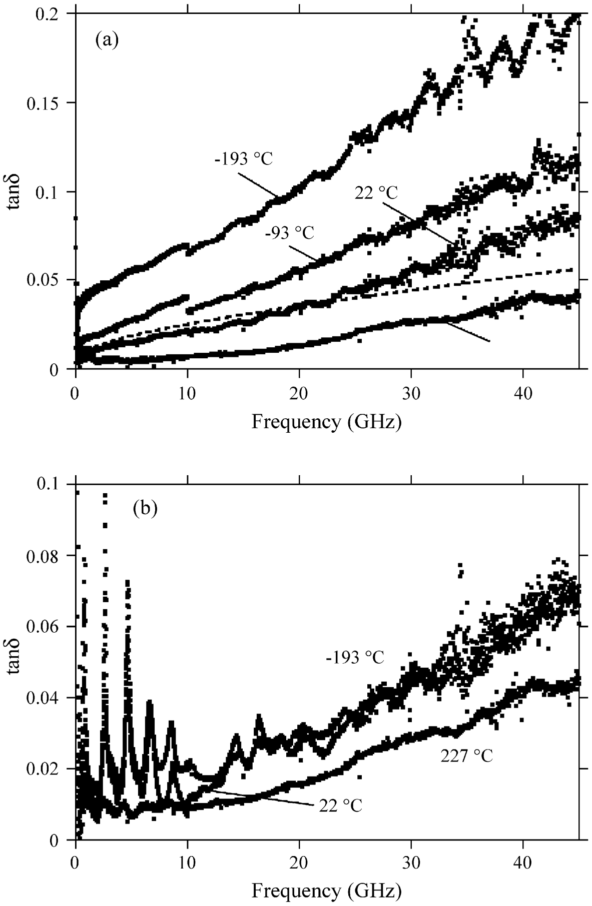

Fig. 3. Loss tangent of a BST varactor vs. frequency at different temperatures without (a) and under 20 V dc bias (b). The dotted line represents the $\tan\delta \propto \omega^{1/3}$ power law.

to frequency dispersion of capacitance caused by relaxation of polarization of local polar regions and/or ferroelectric domains. Fig. 3a shows the loss tangent of a BST varactor versus frequency at different temperatures without dc bias. The dotted line represents the fitting curve for the loss tangent at +22 °C $\tan\delta \propto \tan\delta_{\mathrm{ch}} + \tan\delta_{\mathrm{ph}} + \tan\delta_{\mathrm{ser}}$, where $\tan\delta_{\mathrm{ch}} \propto A\omega^{1/3}$ is the loss associated with charged defects, $\tan\delta_{\mathrm{ph}} = B\omega$ is the intrinsic phonon loss, and $\tan\delta_{\mathrm{ser}} = C\omega$ is the loss associated with electrode series resistance, A is a fitting parameter, and the coefficients $B \approx 3.2 \times 10^{-14}\,\mathrm{Hz}^{-1}$, $C \approx 5.3 \times 10^{-14}\,\mathrm{Hz}^{-1}$.[7] The relatively high discrepancy between the fitting curve and the measured loss tangent above 30 GHz can be attributed to the uncertainty in the frequency independent contact resistance between the microprobe and the capacitor electrode.[12] Fig. 3b shows the loss tangent of a BST varactor versus frequency at different temperatures under 20 V. The resonant peaks in the frequency range 1–10 GHz are caused by resonant conversion of the microwave power into acoustic waves as indicated above.[11] It is clearly seen that the acoustic transformations of the microwave energy are quite extensive at resonance frequencies. Far away from the resonant absorption peaks the microwave-to-acoustic transformation does not contribute substantially to the total microwave losses. Again these effects become negligible at higher temperatures.

At 20 GHz the figure of merit of the varactor,[9] taking into account both the tunability and the loss tangent, is more than 1000 at −193 °C and 50 at +227 °C. The simulated figures of merit of tunable microwave devices (phase shifter, resonator),[8] utilizing ferroelectric varactors, decrease with temperature and frequency. At 20 GHz a phase shifter would reveal a figure of merit more than 200° dB^{-1} at −193 °C and 50° dB^{-1} at +227 °C. A resonator can be tuned in the range up to 20 unloaded bandwidths at −193 °C and 2 unloaded bandwidths at +227 °C. The monotonous temperature dependencies indicate that even at temperatures as high as +227 °C the devices will demonstrate a stable performance. This shows the potential of ferroelectric varactors for application at elevated temperatures. The figure of merit of a phase shifter at 8.5 GHz and +22 °C may be 200° dB^{-1} which is more than two times higher than that of the state of the art device (87° dB^{-1}).[4]

4. Conclusions

The parameters of the high Q-factor BST thin film varactors (capacitance, tunability and loss tangent) have been measured and analyzed at 1 MHz and in wide frequency (45 MHz to 45 GHz), and temperature (−223 °C to +227 °C) ranges. The relative tunability of the capacitance decreases monotonously with temperature from 80 to 90% at −193 °C, down to 10% at +227 °C. The temperature coefficient of capacitance in the temperature range −55 to +125 °C is 0.3% at 20 GHz and zero dc field. The temperature dependence of the varactor loss tangent, in general, follows that of the capacitance. The zero dc field loss tangent of the varactor decreases gradually with temperature and increases with frequency in the microwave region. The monotonous temperature dependencies indicate that even at temperatures as high as +227 °C the devices will demonstrate a stable performance. The loss tangent at zero dc field and 20 GHz is less than 0.1 at −193 °C, and less than 0.02 at +227 °C. The simulated figures of merit of tunable microwave devices (phase shifter, resonator) utilizing ferroelectric varactors decrease with temperature and frequency. At 20 GHz a phase shifter would reveal figure of merit more than 200° dB^{-1} at −193 °C, and 50° dB^{-1} at +227 °C. A resonator may be tuned in the range up to 20 unloaded bandwidths at −193 °C and 2 unloaded bandwidths at +227 °C.

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