

TUNABLE STRONTIUM TITANATE THIN FILMS FOR MICROWAVE DEVICES

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In this paper, strontium titanate (SrTiO₃) thin films on platinized sapphire substrates have been demonstrated as a possible material candidate for tunable microwave device applications. Room temperature capacitance-voltage measurements at 1 MHz demonstrated a tunability of nearly 1.7:1 (41%), with a zero bias quality factor of 342 ($\tan \delta = .00292$). Tunability of 1.75:1 (43%) is achieved with a device quality factor of 146 at 100 MHz. A device quality factor of 40 and a tunability of 1.7:1 (41%) has been obtained at frequencies up to 15 GHz.

Keywords strontium titanate; varactors; microwave loss characterization

INTRODUCTION

Many microwave applications require tunable device characteristics. Phase shifters, delay lines, frequency triplers, tunable filters, and voltage-controlled oscillators are a few examples of such applications. When the device includes a ferroelectric or related material, the nonlinear electric field dependence of the dielectric constant allows the device to be tuned under the application of a bias. As a result, effective phase speed and intrinsic impedance of microwave circuits are modified and frequency and phase of the microwave device is tuned.

Many researchers are investigating the incorporation of ferroelectrics in to frequency agile components [1]-[7]. Devices made of ferroelectric materials are expected to have high tunability, low microwave loss, fast switching time, high power handling capacity, and low DC power requirements. Barium strontium titanate ($\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3$ or BST) thin films have been studied extensively for room temperature applications [1]-[4]. Different device tunabilities and microwave losses are reported for BST films. A figure of merit

$$K = \frac{\Delta\epsilon}{\epsilon \tan\delta} \quad (1)$$

has been defined for ferroelectric devices to allow comparison of different films using tunability and loss. In this equation, $\tan\delta$ denotes the device loss tangent, which is the inverse of device quality factor whereas the device tunability is expressed in terms of percentage change in the dielectric constant. We also use a more convenient definition of tunability throughout this paper

$$\frac{\epsilon_{\max}(V=0)}{\epsilon_{\min}(V=V_b)} \quad (2)$$

where the breakdown voltage V_b is the voltage at which the loss tangent increases sharply. As it can be seen from (1), improvements in the device tunability and loss tangent will result in a higher figure of merit.

Strontium titanate films (STO) lowering the loss tangent of microwave strontium titanate has a lower loss tangent has been shown to have tunability at low frequencies. These devices have been integrated with high temperature ferroelectric materials to form low-loss tunable microwave components.

In this work, we studied strontium titanate thin films deposited on platinumized sapphire substrates. Room temperature measurements on discrete tunable capacitors are presented and we discuss the potential of distributed parameter devices using thin film technology.

DEVICE CHARACTERIZATION

SrTiO_3 thin films were deposited from a solution in an rf magnetron sputtering system. The SrTiO_3 deposited on an (0001) oriented sapphire substrate. Platinum was deposited as the bottom layer by sputtering followed by 135 nm SrTiO_3 sputtering in situ.

Low Frequency Measurements

Coplanar capacitors fabricated with thin films on sapphire substrates techniques were used to perform low frequency measurements. An Agilent 4294A Variable Frequency Impedance Analyzer with a 200 mV probe was used to do impedance measurements as a function of frequency. Measured impedances are fitted in to a parallel RLC circuit to find capacitance and loss tangent.

The dielectric constant of the pure SrTiO_3 is 140 with a zero bias quality factor of 146. Figure 1a shows the field dependence of the dielectric constant at 100 MHz at room temperature. It can be seen that a tunability of 1.7:1 (41%) has been achieved. Figure 1b shows the loss tangent results at 100 MHz. Tunability of the loss tangent is 1.7:1. The device quality factor of 146. At low

Strontium titanate films (STO) are promising candidates for lowering the loss tangent of microwave devices. Bulk single crystal strontium titanate has a lower loss tangent than BST. STO films have been shown to have tunability at low temperatures [5]-[7]. STO films have been integrated with high temperature superconductors (HTS) for low-loss tunable microwave components [5].

In this work, we studied strontium titanate films deposited on platinized sapphire substrates. Results of room temperature measurements on discrete tunable capacitors are presented. We also discuss the potential of distributed phase shifter circuits using STO thin film technology.

DEVICE CHARACTERIZATION

SrTiO₃ thin films were deposited from a stoichiometric SrTiO₃ target in an rf magnetron sputtering system. The data reported here are for SrTiO₃ deposited on an (0001) oriented sapphire substrate. 100 nm of platinum was deposited as the bottom electrode by dc magnetron sputtering followed by 135 nm SrTiO₃ deposited by rf magnetron sputtering in situ.

Low Frequency Measurements

Coplanar capacitors fabricated with standard photo-lithographic techniques were used to perform low-frequency measurements. An Agilent 4294A Variable Frequency (40 Hz-110 MHz) Precision Impedance Analyzer with a 200 mV oscillating electric field was used to do impedance measurements as a function of frequency and voltage. Measured impedances are fitted in to a parallel capacitance model to find capacitance and loss tangent.

The dielectric constant of the pure SrTiO₃ film was measured to be 140 with a zero bias quality factor of 342 ($\tan \delta = .00292$) at 1 MHz. Figure 1a shows the field dependence of the capacitance and loss at 1 MHz at room temperature. It can be seen that a tunability of nearly 1.7:1 (41%) has been achieved. Figure 1b shows the measurement results at 100 MHz. Tunability of 1.75:1 (43 %) is achieved with a device quality factor of 146. At low

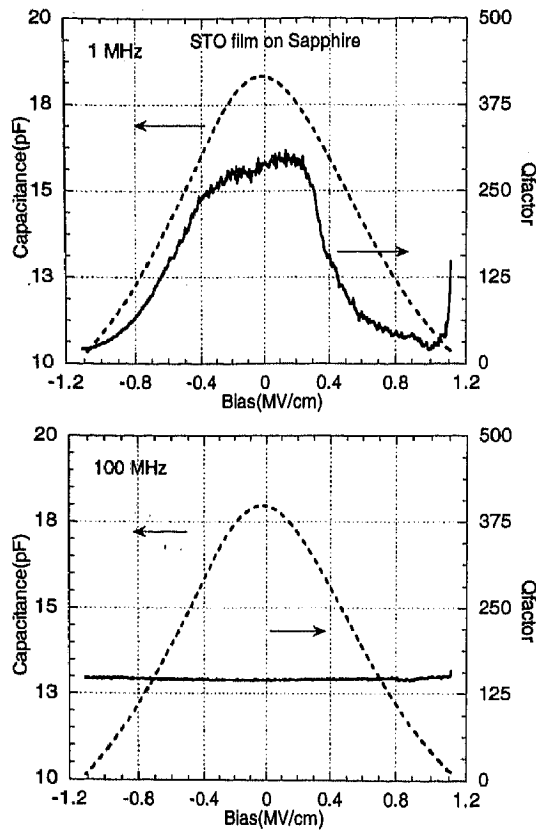


FIGURE 1a-b Capacitance and quality factor measurements for STO capacitors at 1 MHz and 100MHz.

frequencies, the leakage losses in the material limit the overall device quality factor. As operation frequency is increased, the material leakage losses decrease. However, the device quality factor is limited by metal losses at high frequencies. We calculated the metal quality factor to be around 180 at 100 MHz using the capacitor geometry, which is in good agreement with the measured overall device quality factor. Figure 2 shows loss measurement as a function of frequency at

zero bias. Leakage and metallic loss
Fig. 2.

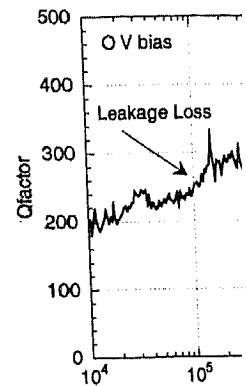


FIGURE 2 Pt/STO/Pt loss measurement as a function of frequency at zero bias.

High Frequency Measurements

For the characterization of the parallel plate capacitors were 0.15-2pF. Parallel plate geometry low voltages relative to inter-electric fields are better confined fabricated using standard monolayer

To investigate their performance capacitors were measured with a network analyzer. The device was calibrated using on-wafer measurements were made on the end of CPW lines at different frequencies recorded from 50MHz to 40 GHz. The circuit structures to correctly model the STO capacitor and thin film equivalent circuit model as extracted quality factor values. The capacitors had a quality factor of 41% was demonstrated. For different bias voltages.

zero bias. Leakage and metallic loss mechanisms can be seen clearly in Fig. 2.

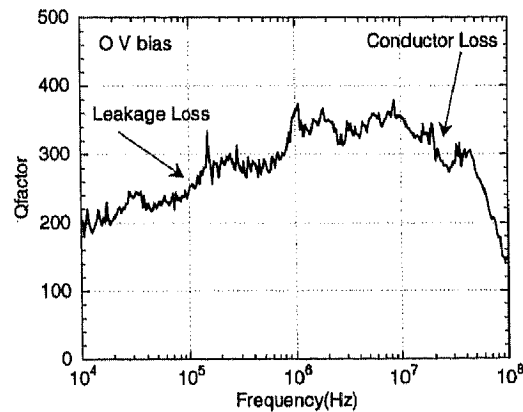


FIGURE. 2 Pt/STO/Pt loss measurements at zero bias voltage.

High Frequency Measurements

For the characterization of the STO film at microwave frequencies, parallel plate capacitors were fabricated with capacitance values of 0.15-2pF. Parallel plate geometry enables a higher tunability at very low voltages relative to interdigital capacitor structures since the electric fields are better confined in the film. The test structures were fabricated using standard monolithic fabrication techniques.

To investigate their performance at microwave frequencies, STO capacitors were measured with an HP 8722D network analyzer that was calibrated using on-wafer standards. The one-port S_{11} measurements were made on test structures that were mounted at the end of CPW lines at different bias voltages. The s-parameters are recorded from 50MHz to 40 GHz. The wafer included open and short circuit structures to correctly account for the pads and parasitics. The STO capacitor and thin film properties were extracted using an equivalent circuit model as outlined in ref. [8]. Figure 3a shows extracted quality factor values for the discrete device. Discrete capacitors had a quality factor of 40 up to 15GHz. A tunability of 1.7:1 (41%) was demonstrated. Fig. 3b shows STO capacitance values at different bias voltages.

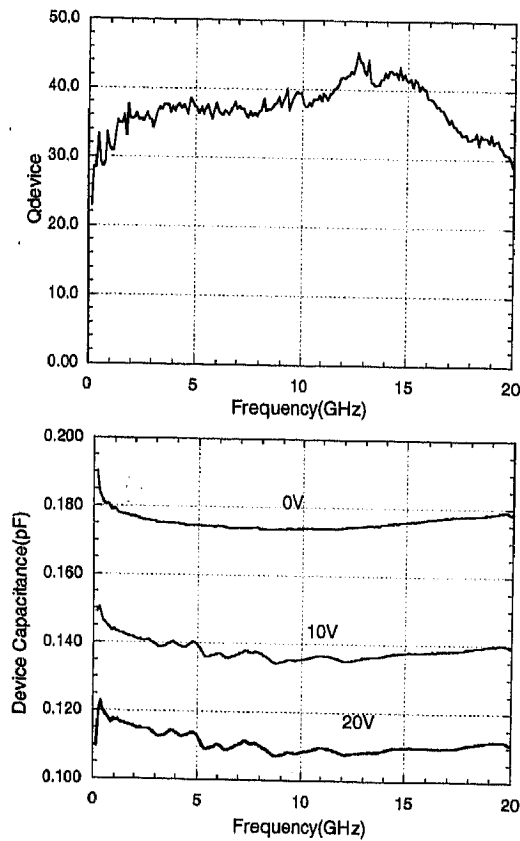


FIGURE 3a-b High frequency loss and tunability measurements. STO discrete varactors had a quality factor of 40 and 1.7:1 tunability at 15 GHz.

Distributed Phase Shifters Using STO Thin Films

Phase shifters are largely used in modern phased array antenna systems. Low loss and inexpensive microwave phase shifters are required to reduce the cost of these systems to ensure widespread application. STO thin film technology is a possible candidate for use in phase shifter applications as demonstrated in this work. For different

material systems, we simulated optimal designs to get 360° differential phase shift with low insertion loss at 20 GHz, as outlined in [9]. The figure of merit (differential phase shift divided by insertion loss) as a function of tunability for different device designs depends strongly on both the device quality factor and the tunability. It is possible to obtain a better figure of merit with high quality factor even if the tunability is low. Our STO devices should yield a figure of merit that is much higher, improving device performance.

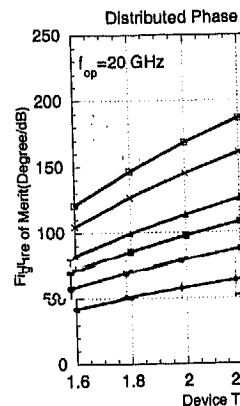


FIGURE 4 Simulated figure of merit (differential phase shift divided by insertion loss) for distributed phase shifters using STO thin films on sapphire at 20 GHz.

CONCLUSIONS

This work has demonstrated that STO is a good candidate as material used in tunable phase shifters. Tunable strontium titanate in thin film form has good loss characteristics up to

material systems, we simulated optimum distributed phase shifter designs to get 360° differential phase shift with minimum insertion loss at 20 GHz, as outlined in [9]. In Fig. 4, the phase shifter figure of merit (differential phase shift divided by insertion loss) is plotted as a function of tunability for different device quality factors. Insertion loss depends strongly on both the device quality factor and tunability and it is possible to obtain a better figure of merit with a higher device quality factor even if the tunability is lower. STO and different BST films can be interpolated on this plot with their given performances. Our STO devices should yield a figure of merit $\sim 85^\circ/\text{dB}$ at 20 GHz by improving device performance.

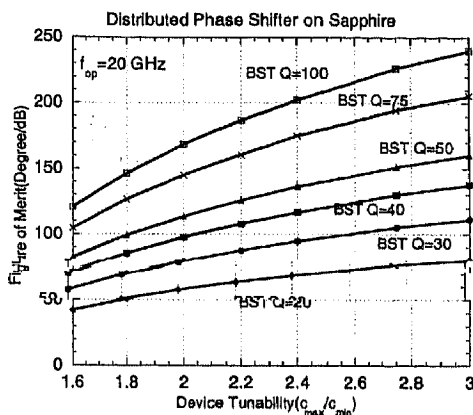


FIGURE 4 Simulated figure of merit (differential phase shift divided by insertion loss) for distributed phase shifter circuits on sapphire at 20 GHz.

CONCLUSIONS

This work has demonstrated that pure strontium titanate is a viable candidate as material used in varactors for microwave circuits. Tunable strontium titanate in thin film form has been demonstrated with good loss characteristics up to 15 GHz.

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PROGRESS IN ECONOMICAL BASED ON THIN FERROELECTRIC

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A considerable amount of work has been done on the design and phase agile microwave circuitry. The best films to date have been laser ablated. But laser ablation is not suitable for volume manufacturing, partly because of the large 5 cm diameter wafers or small diameter wafers. Commercialization is testing. Testing of phase shifters must be inserted into a fixture to insert the phase shifter. High voltage bias tees are not common in microwave instrumentation. We are testing new methods including MOCLD, CCVD, and on-wafer testing approach for sputtered films. Results are reported in a companion paper. Sputtered PLZT films on LaAlO₃ substrate in the K-band produced a figure of merit of 18°/dB. Two of the best laser ablated BaTiO₃ films are uncharacteristically flat frequency shifters. Considering the large lattice mismatch, the film crystallinity is very good as measured by XRD. Films also appeared to be cubic. Ba_{0.57}Sr_{0.43}TiO₃ on sapphire. 20°/dB. Figure of merit of 18°/dB. Finally we report on the coplanar-to-microstrip transition. Devices that pass tested on wafer. Devices that pass tested on wafer. Devices that pass tested off so the phase shifter can