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## Reliability and Stability of Novel Tunable Thin Film

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### ABSTRACT

A new process has been developed in Paratek Microwave Inc. to formulate stable tunable (Ba, Sr)TiO<sub>3</sub> (BST) based thin film material. Varactors, with a co-planar structure, were fabricated by using the new material. The varactor Q of 105 tested at 2 GHz was observed with average tunability of 58 % at 150V (37.5 V/μm). The lifetime tests indicated that this material is very stable under continuous 100 to 150 V dc bias both at the room temperature and in 70 °C environment. Thus, this novel tunable thin film material opens a new avenue to develop high quality tunable microwave devices. Tunable IF filters have been built by using this novel material for microwave backhaul radios and handset applications. Initial results of a RF phase shifter are also included and demonstrate another application of these films.

### INTRODUCTION

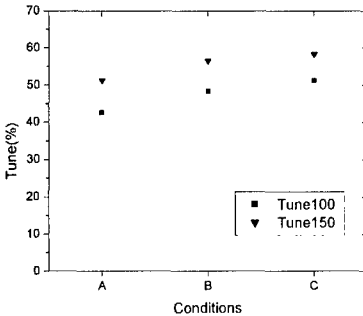
Voltage-tunable devices, such as phase shifters, tunable filters and voltage-controlled oscillators, are highly desirable in RF and microwave applications. Currently, most these tunable devices are based on ferrite materials and semiconductor diode varactors. Ferrite tunable devices have problems of low tuning speed and high cost. On the other hand, diode varactors show low Q (especially at frequency > 2 GHz), low power handling and high intermodulation distortion.

Recently, voltage tunable (Ba, Sr) TiO<sub>3</sub> (BST) materials have been extensively investigated, due to their high power handling, low loss, rapid tuning, and high tolerance to burnout over a wide frequency range [1-5]. Thin films of BST type materials are desirable, because they can be easily integrated with standard IC processing and can therefore be scaled for mass production [6-9]. However, there are some problems that need to be solved before these materials can be used for the above-mentioned applications. These problems include leakage current development and capacitance drift during the dc bias. It was reported that various kinds of defects, such as oxygen vacancies, in the films might cause leakage current as well as the degradation of loss tangent. The development of leakage current directly results in short lifetime of the films. The capacitance drift can cause device or system error and stability problems. Paratek has developed a group of Parascan<sup>TM</sup> tunable microwave materials. New processes and new-doped BST thin films have been developed, to solve the above-mentioned problems of BST thin film materials. In this paper, we present the experimental results of extensive testing of the microwave properties, lifetime and stability of fabricated varactors. The performance of RF devices, such as tunable filters and phase shifters, implementing this material are also shown. The results show promising properties of thin film Parascan<sup>TM</sup> materials in the application of commercial microwave tunable devices.

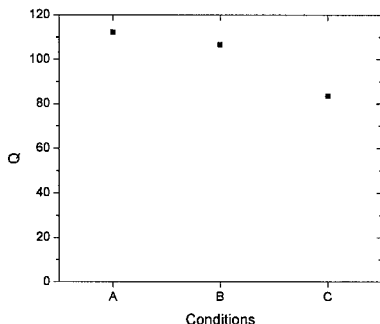
## EXPERIMENT RESULTS AND DISCUSSION

Thin film varactors were fabricated by means of pulsed laser (KrF excimer laser) deposition using doped BST targets. The targets were fabricated at Paratek by using traditional ceramic process. The doping elements include tungsten, MgO and others. The films were deposited onto a variety of substrates such as MgO, sapphire and polycrystalline  $\text{Al}_2\text{O}_3$ . The doped BST thin films were deposited at a temperature range from 25 °C to 800 °C, and under oxygen pressures between 100 to 400 mtorr. A thin buffer layer may be inserted between the substrate and the main part of the thin film. Post annealing was accomplished in an environment of oxygen or air. Typical film thickness was 3000 Å to 5000 Å, measured by a step profilometer. Co-planar structures, both single gap and interdigitated electrode (IDE) patterns, were fabricated to build the varactors. The thickness of top gold electrodes was between 2 to 3 microns. The typical gap sizes ranged from 2 to 6 microns. The finger numbers were varied to reach required capacitance. The data presented here is mostly from IDE type varactors with a 4 microns gap deposited on MgO substrate. Varactors were tested at a frequency of 2 GHz by using an HP 8722ES Network Analyzer with a calibrated fixture. The bias voltage was applied and the leakage currents were measured by means of a Keithley 487 Picoammeter/voltage source.

Testing results for three typical batches of BST films, fabricated in different processes and using different Parascan<sup>TM</sup> materials are shown in Figs. 1-3. Fig. 1 shows the tuning, defined as  $(C_p(0 \text{ Volt}) - C_p(\text{Bias Volt}))/C_p(0 \text{ Volt})$ , for these three BST batches at two bias voltages. Each data point in the figure represents an average value of all varactors in the testing batch. The tuning at 150V is generally 10 to 15% higher comparing to that at 100V. The average tuning at 100 V reaches 51%, and reaches 58% at 150 V. Fig. 2 shows the average Q value for the same batches of samples at 0 bias voltage. The average Q reaches 110 for one batch of BST films. Normally, Q slightly increases with increasing bias voltage for good quality varactors. Fig. 3 shows an average figure of merit (FOM) for these three batches of samples. In this figure, FOM is calculated by tunability (150V)  $\times$  Q (0). The average FOM is more than 6000 for one-batch of BST varactors.



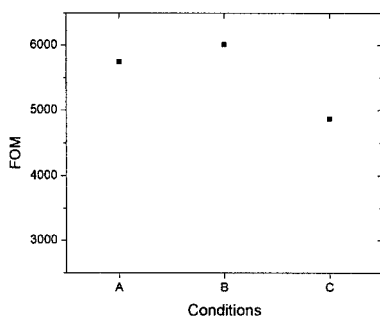
**Fig. 1.** Average tuning at two bias voltages, 100V (25 V/ $\mu\text{m}$ ) and 150 V (37.5 V/ $\mu\text{m}$ ), measured at 2 GHz, for three different batches of samples.



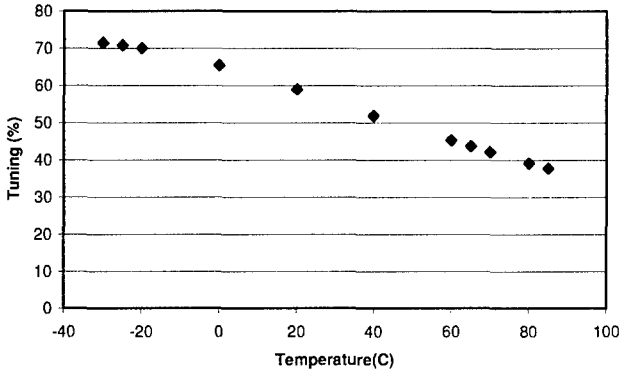
**Fig. 2.** Average Q value, measured at 2 GHz and 0 volt bias, for three different batches of samples.

The varactors were also tested over a wide temperature range from  $-30^{\circ}\text{C}$  to  $85^{\circ}\text{C}$ . The selection of this temperature range is based on common RF device requirements. Figure 4 shows tunability, measured at 150V of biasing, as a function of test temperature. Tuning generally drops as the temperature increases. As high as 40% of tuning is observed at the temperature of  $80^{\circ}\text{C}$ . At low temperature ( $-20^{\circ}\text{C}$ ), the tuning reaches more than 70%. The Q is also temperature related. The Q value increases as the temperature rises.

Stability is an important topic for the RF application of thin film BST based material. Increase in leakage current and decrease in  $C_p$  and tuning are two related phenomena. It is our understanding that the stability of thin film varactors is related to both the bulk part of thin film and the two interfaces. These interfaces are the interface between film and substrate and the interface between the film and the metal electrodes. The properties of both the bulk part of



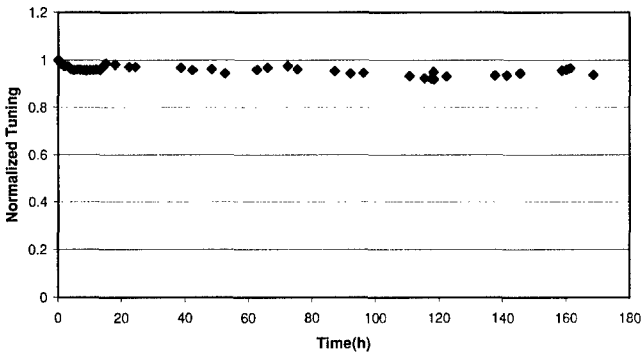
**Fig. 3.** Figure of Merit (FOM), calculated by tunability (150V)  $\times$  Q (0) and measured at 2 GHz, for different batches of samples. The average FOM reaches more than 6000 for batch B samples.



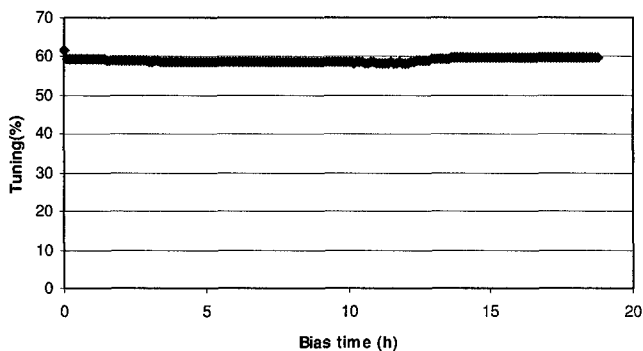
**Fig. 4.** Tuning at 150 V (37.5 V/ $\mu\text{m}$ ), measured at 2 GHz, as a function of temperature.

material and the two interfaces relate to thin film material itself as well as the device fabrication processes. So we need to optimize both the composition and the associated processing to improve the stability of varactors. Generally, a decrease in tuning from 8 – 20 %, has been observed for BST thin film devices. The method of initial burn out has been previously suggested to compensate this tuning degradation.

Our process has improved the tuning stability. As a typical example, a varactor was biased at 100V continuously for 170 hours. Fig. 5 shows the normalized tuning at 100V, i.e.,  $\text{Tuning}(t)/\text{Tuning}(0)$ , as a function of bias time. The data indicated that this varactor is stable



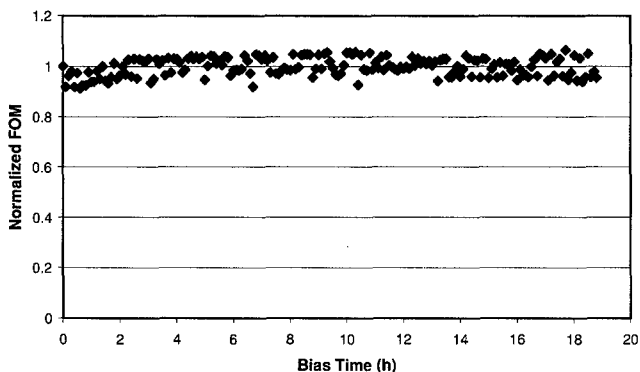
**Fig. 5.** Normalized tuning as a function of bias time. The test varactor was biased at 100 V (25 V/ $\mu\text{m}$ ) constantly.



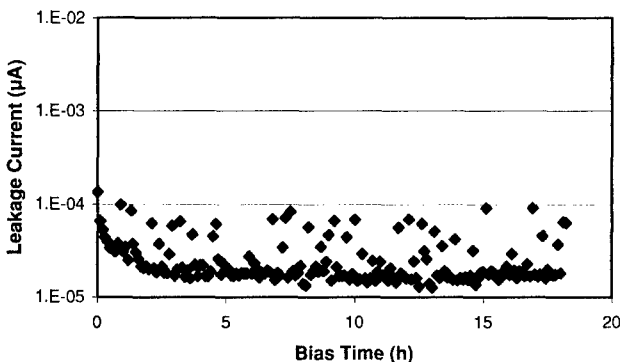
**Fig. 6.** Tuning as a function of bias time. The test varactor is biased at 150 V (37.5 V/ $\mu$ m) constantly.

under long -term biasing conditions. The tuning decreased about 5 to 7 % during the 170 hour time period. No leakage current was developed during this experiment.

The stability was improved when specific dopants were incorporated into the thin film devices. Fig. 6 and Fig. 7 show the results. The varactor was biased at 150V continuously for 18 hours, and the tuning at 150 V and Q were tested. Fig. 6 shows tuning as a function of bias time. Tuning decreased less than 4% in the first 6 minutes. Then, it became stable for the remaining experimental time period. Fig. 7 shows the normalized FOM, defined as  $\text{tunability}(150\text{V}, t) \times Q(0\text{V}, t) / \text{tune}(150\text{V}, 0) \times Q(0\text{V}, 0)$ , as a function of dc bias time. Considering the experimental variation of Q value, the FOM is stable the entire 18 hours with constant 150 V of applied dc bias.



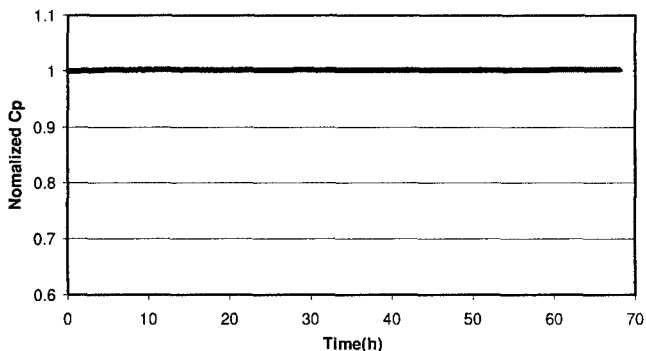
**Fig. 7.** FOM variation as a function of bias time.



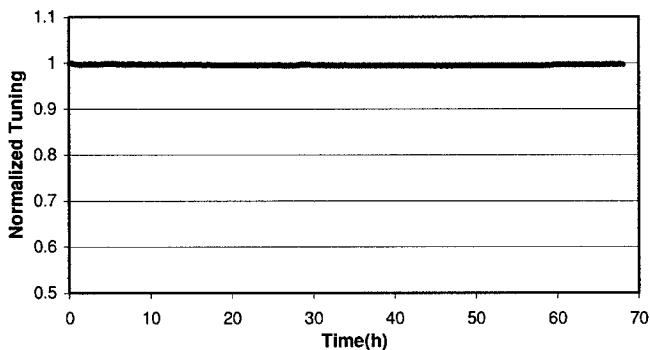
**Fig. 8.** Leakage current measured at 150 V (37.5 V/ $\mu\text{m}$ ) as a function of bias time. The varactor was constantly dc biased at 150 V.

The leakage current was also measured while the varactor was continuously biased. For a good quality varactor, the leakage current is stable, with a value well below  $10^{-4}$   $\mu\text{A}$ , under 150 V of applied bias. Fig. 8 shows a typical leakage current behavior at 150 V bias for 18 hours. The leakage current was measured each 6 minutes under 150V of applied dc bias. The leakage currents  $I(150)$  dropped from  $10^{-4}$   $\mu\text{A}$  to  $2 \times 10^{-5}$   $\mu\text{A}$  in the first three hours. Then, it became stable during the remaining experimental time period.

The lifetime behavior at 70  $^{\circ}\text{C}$  was also measured. The sample varactor and its testing fixture were kept in a temperature chamber at 70  $^{\circ}\text{C}$ . The varactor was continuously dc biased at 100 V. The  $C_p$  measurements at 50 V and 100 V were taken automatically every 15 minutes.



**Fig. 9.** Normalized  $C_p$ , measured at 50 V bias, as a function of time. The varactor and its fixture were kept in a temperature chamber of 70  $^{\circ}\text{C}$ .



**Fig. 10.** Normalized tuning, from 100 V to 50 V, as a function of bias time. The varactor and its fixture were kept in a temperature chamber of 70 °C.

The experimental results are shown in Fig. 9 and 10. Fig. 9 shows the normalized Cp variation, measured at 50 V, as a function of biasing time. The Cp variation in the 68-hour experiment is less than 0.3 %. The Cp variation at 100 V is less than 0.4 %. Both the Cp variations (at 50V and 100V) fall within the experimental error range of the measurement equipment. Thus, the Cp, measured from 50 V to 100 V, is extremely stable in the temperature of 70 °C, as the varactor is constantly biased at 100 V. Fig. 10 shows the normalized tuning as a function of bias time. The observed maximum tuning drop, in the whole experimental period, is 0.6 %, which is also within the experimental error range of the measurement equipment. Figs. 9-10 indicate stable characteristics of varactors fabricated by our new processes and new materials at 70 °C.

Tunable IF filters that incorporating this novel material have been fabricated and tested. The IF tunable filter is constructed using a 4-pole microstrip structure, and operates at 2 GHz with bandwidth of 50 MHz. The filter can cover a tuning range of 300 MHz frequency at a temperature range of 0 °C to 65 °C. The insertion loss of the filter is 4.2 dB to 5.2 dB with return loss of better than 20 dB in the tuning range.

A phase shifter, with a 90 degree phase change was fabricated at Paratek by using the varactors made from our new thin film processes. The initial results indicated that the insertion loss of the phase shift, induced by thin film varactors, was 0.25 dB at all bias conditions at 2.4 GHz. Thus, our new process also opens a potential avenue for microwave antenna applications.

## CONCLUSIONS

Our new-doped Parascan™ BST based thin film has high tunability and high Q. The varactor Q of 105 tested at 2 GHz, was observed with an average tunability of greater than 40% at 70 °C. The lifetime test results indicate that this material is very stable at both the room temperature and 70 °C environment. Leakage current less than  $2 \times 10^{-5}$   $\mu$ A was achieved under constant dc biasing of 37.5 V/ $\mu$ m. Tunable filters and phase shifters have been fabricated using these thin film varactors. These devices demonstrated the advantage of a simple structure, small



size, low cost, low bias voltage and low loss. Thus, this novel tunable thin film material opens a new avenue to develop high quality tunable microwave devices.

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