Intrinsically Switchable Interdigitated Barium Titanate Thin Film Contour Mode Resonators

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***Abstract* — This paper presents the design and measurement results of an intrinsically switchable interdigitated contour mode resonator based on barium titanate (BTO) thin films. The device exhibits quality factors of 178 and 152 at series and parallel resonance frequencies of 1.67 and 1.68 GHz, respectively, with the application of a 10 V dc bias. Resonances are turned off without the application of dc bias. This is the first demonstration of an intrinsically switchable interdigitated ferroelectric contour mode resonator.**

***Index Terms* — Barium titanate, ferroelectric devices, interdigitated contour mode resonators, intrinsically switchable, radio-frequency (RF) microelectromechanical systems (MEMS).**

I. Introduction

One of the goals of future mobile communication systems is to implement software defined and cognitive radios. Such systems would have two modes of operation. In the first mode, the radio would arbitrarily switch its carrier frequency and communication protocol to match that of a particular radio, enabling it to communicate to any wireless device as well as take advantage of existing wireless infrastructure. In the second mode, the radio would communicate to another similar radio and would choose a carrier frequency and communication protocol that maximizes bandwidth and energy efficiency while minimizing the amount of interference and noise added to the signal. As the quality of communication link changes due to various factors such as fading, the carrier frequency and communication protocol would change in real time to maintain the quality of the link. Such a system may also choose to sporadically switch between carrier frequencies and communication protocols with encryption to prevent eavesdropping for military use while also having the ability to access civilian channels. Similar systems, such as the Thales 25, already exist [1]. However, such systems are very cumbersome, impractical, and unattainable for the majority of users.

The work presented in this paper is intended to make software defined radios and cognitive radios more practical. This is done by addressing the challenge of achieving frequency agility in order to switch the frequency band and channel of operation. The two main approaches to achieving frequency agility are to use either tunable or switchable frequency devices and components. This work addresses the design of switchable resonators, which can be used to design switchable filters and other switchable frequency components.

Previously, intrinsically switchable film bulk acoustic wave resonator (FBAR) filters using ferroelectric thin films have been demonstrated operating at a center frequency of 2.14 GHz [2]. An array of such filters can be used to design switchable RF filterbanks. However, since FBARs that make up the filters are thickness mode devices, each element of the filterbank would require a different film thickness, which increases the complexity of the design as more elements are added. To overcome this issue, one could replace the FBARs in the filters with lateral mode, or contour mode resonators, which have a series resonant frequency defined by its lateral dimensions. An example of such a resonator is found in [3], which demonstrates an intrinsically switchable ring-shaped contour mode resonator based on barium titanate (BTO) with a series resonance frequency of 160 MHz. However, ring-shaped and rectangular-plate lateral mode resonators are limited to lower frequencies since the average radius to annular width ratio of the ring shaped resonator and aspect ratio of the rectangular plate resonator increases to unfeasible values at microwave frequencies [4]. In this paper, an intrinsically switchable interdigitated contour mode resonator operating at GHz frequencies is demonstrated.

II. Design

To achieve contour mode resonators that operate in the GHz range, an interdigitated structure was chosen. This structure has many advantages such as increased robustness and suppressed spurious responses [5]. Moreover, the resonance frequency is lithographically defined by the electrode patterning and is only limited by the minimum feature size of the process.

The designed interdigitated contour mode resonator consists of a thin film of BTO sandwiched between two layers of interdigitated platinum electrodes as shown in Fig. 1. It is excited by applying an RF signal and dc bias through a coplanar waveguide.

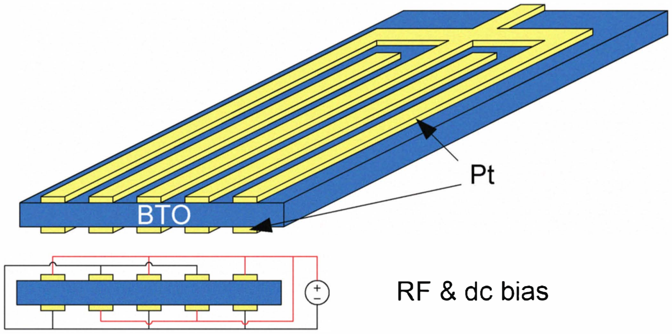

Fig. 1. Cross sectional view of an interdigitated high frequency contour mode resonator and an illustration showing the signal path and biasing configuration.

In order to achieve resonance in the GHz range, it is necessary to make the periodicity of the interdigitated electrodes very small. The approximate series resonant frequency of the structure can be calculated by using (1) with the parameters defined below [5].

$$f_s \approx \frac{\sqrt{E_{BTO} / \rho_{BTO}}}{2W_{res}\Phi} \tag{1}$$

$$\Phi = 1 + \frac{W_{non-elec}}{W_{elec}} \cdot \sqrt{\frac{1+\frac{t_{Pt}\rho_{Pt}}{t_{BTO}\rho_{BTO}}}{1+\frac{t_{Pt}E_{Pt}}{t_{BTO}E_{BTO}}}}$$

E_{BTO} = BTO Poisson's ratio
t_{BTO} = BTO thickness
ρ_{BTO} = BTO mass density
W_{elec} = electrode width
W_{res} = electrode periodicity
E_{Pt} = Pt Poisson's ratio
t_{Pt} = Pt thickness
ρ_{Pt} = Pt mass density
$W_{non-elec}$ = electrode separation

Simulations have also been performed using COMSOL to determine the series resonance frequency of interdigitated contour mode resonators with equal electrode widths and electrode separations. The simulation was performed using the piezoelectric properties of BTO. Results show a prominent series resonance at 1.67 GHz for an electrode width of 1.0 µm.

III. Fabrication

The interdigitated contour mode resonators are fabricated on high resistivity silicon substrates that are 525 µm thick and have a resistivity of 3kΩ·cm. Fabrication begins by thermally growing a 100 nm layer of SiO_2 on the wafer. A 100 nm platinum bottom electrode is then patterned by e-beam evaporation and liftoff. The SiO_2 is etched to create silicon release windows using buffered hydrofluoric acid. A 350 nm BTO thin film is deposited by pulsed laser deposition (PLD) using an excimer laser (λ = 248 nm, 25 ns pulse width, 5 Hz) with substrate temperature of 650 °C in a 300 mTorr oxygen environment. The top electrode is deposited using the identical procedure as with the bottom electrode. The BTO is then etched in two separate steps. The first step is done with diluted hydrofluoric acid for creating a via to short the top and bottom electrodes of the resonator tethers. The second step is performed on a LAM 9400 system for creating the release windows as well as defining the resonator dimensions. A 500 nm gold contact layer with a 50 nm titanium adhesion layer is deposited for the CPW also using e-beam evaporation. Finally, the devices are released using XeF_2. A micrograph of a device is shown in Fig. 2.

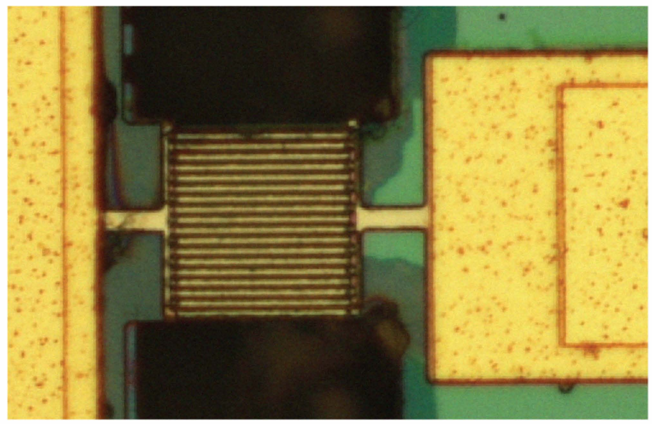

Fig. 2. Micrograph of an interdigitated high frequency contour mode resonator.

IV. Experimental Results

The fabricated high frequency contour mode resonators are measured with 150 µm pitch size GSG probes. S-parameters are obtained by using an Agilent E8364B vector network analyzer. The input impedance of the resonator is measured as the dc bias voltage applied to the resonator is gradually increased. In the absence of a dc bias, the response is capacitive while with a 10 V dc bias, two strong resonances occur, as seen in Fig. 3 and Fig. 4.

At the design frequency of the resonator, measured to be 1.67 GHz for the series resonance and 1.68 GHz for the parallel resonance, the quality factors are 149 and 143, respectively, by using (2). By de-embeding the parasitics of the contact pads, the intrinsic device quality factors increase to 178 and 152 for the series and parallel resonance frequency, respectively. De-embeding was performed by simulating the components of the device that were not part of the actual resonator structure in an electromagnetic solver. The simulated model includes all the metal layers which made up the contact pads as well as the influence of the SiO_2 layer and high resistivity silicon wafer below them. The extracted results were then used in an electronic design software to subtract the parasitic effects of the contact pads from the measured quality factors to obtain the intrinsic resonator quality factors.

The effective electromagnetic coupling coefficient (K_t^2) is calculated to be 2.0 % by using (3) [3], which is comparable to that of aluminum nitride interdigitated contour mode resonators [5]. A second resonance mode also occurs in the on state of the device, as seen in Fig. 3 and Fig. 4. This response is attributed to the thickness mode resonance of the device.

$$Q = \frac{f}{2}\frac{d\phi_{Zin}}{df} \tag{2}$$

$$K_t^2 = \frac{\pi}{2}\frac{f_s}{f_p}\tan\left(\frac{\pi}{2}\frac{(f_p - f_s)}{f_p}\right) \tag{3}$$

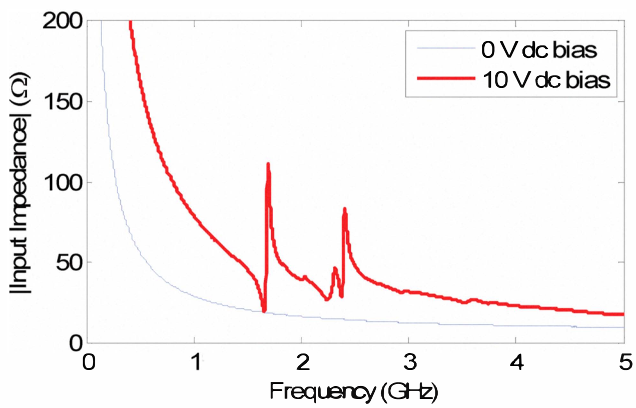

Fig. 3. Measured |input impedance| of the interdigitated contour mode resonator in the on and off state.

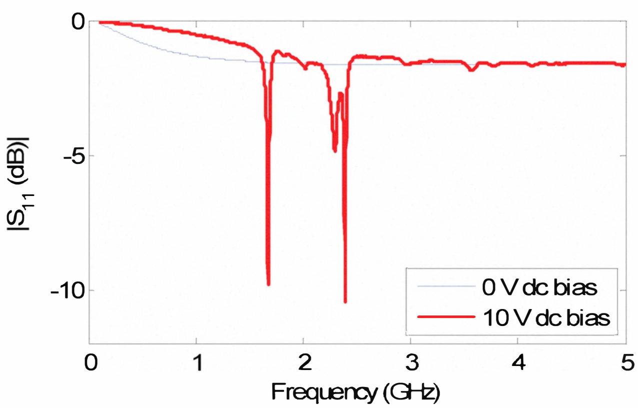

Fig. 4. Measured $|S_{11}|$ of the resonator in the on and off state. In the on state. Minima occur at 1.673 and 2.389 GHz, which correspond to the contour mode and thickness mode resonances, respectively.

This is the very first demonstration of an intrinsically switchable interdigitated ferroelectric contour mode resonator. The quality factor and effective electromechanical coupling coefficient can be improved by investigating the use of alternative metals for the electrodes, refining the processing techniques for depositing and etching the ferroelectric thin film, as well as optimizing the geometry, thickness and various other parameters of the device.

VII. Conclusion

The first demonstration of interdigitated contour mode bulk acoustic wave resonators based on ferroelectric BTO thin films have been designed, fabricated, and characterized. The resonators can be intrinsically switched on and off by applying a dc bias voltage. Our experimental results show a strong resonance at 1.67 GHz. Future work will include improving the quality factor of the resonators by studying both the electrical and acoustic properties of the deposited layers and how their losses can be decreased. The geometry of the resonators may also be optimized for improved performance. Film thicknesses, number of fingers will also be explored for improving the effective coupling coefficient.

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