Intrinsically Switchable Contour Mode Acoustic Wave Resonators Based on Barium Titanate Thin Films

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***Abstract* — This paper summarizes the design, fabrication, and performance of an intrinsically switchable contour mode acoustic wave resonator using the ferroelectric material barium titanate ($BaTiO_3$ or BTO). The resonance frequency of contour mode resonators is mainly determined by its lateral dimensions. Because of the electrostrictive effect in BTO thin films, the acoustic resonance can be turned on by the application of a DC bias voltage. The BTO contour mode resonator has series and parallel resonance frequencies of 159.7 MHz and 160.45 MHz, respectively, when biased at 12 V. The quality factors for the series and parallel resonance frequencies are 47 and 83, respectively.**

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

I. Introduction

Future wireless communication systems demand frequency agility for multi-band operation and/or better spectrum utilization. Frequency controlling components such as resonators and filters have an enormous impact on the design of such systems. To realize low cost and compact multi-band wireless communication devices, monolithic integration of switchable resonators and filter banks on a single wafer is necessary. However, current resonator and filter technologies possess major shortcomings such as excess power consumption, signal loss, and circuit complexity.

Surface acoustic wave (SAW) resonators [1] and film bulk acoustic wave resonators (FBAR) [2] have been commercially successful over the last decade. SAW resonators and FBARs based on the piezoelectric material aluminum nitride (AlN) have been used to make filters that exhibit low insertion loss and high quality factors. However, using AlN based filters to realize switchable filter banks require external switches. This approach is not ideal since it results in additional loss, complexity, and power consumption. Vibrating micromechanical resonators can be switched on and off by the application of a DC bias voltage [3]. They have been demonstrated with quality factors above 10,000. However, they have difficulty interfacing with standard 50 Ω RF systems due to their large motional resistance [4].

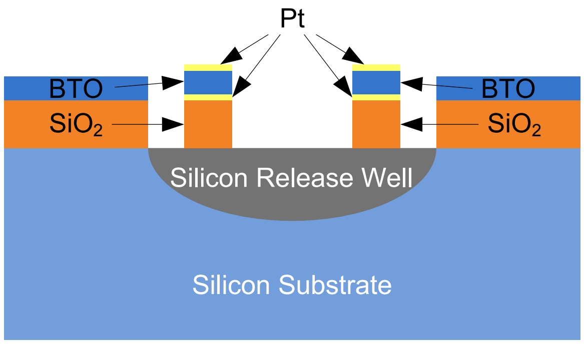
DC electric field induced piezoelectricity and electrostriction have recently been reported in ferroelectric thin films [5, 6]. Intrinsically switchable acoustic wave resonators can be realized using ferroelectric thin films. For example, a switchable FBAR using $Ba_{0.5}Sr_{0.5}TiO_3$ thin films has been demonstrated with quality factors exceeding 200 at 2 GHz [7]. Furthermore, solidly mounted resonators (SMR) using $SrTiO_3$ and BTO thin films have been reported with quality factors of 78 and 30 at 5.8 GHz and 4 GHz, respectively [8, 9]. Both FBARs and SMRs are thickness mode resonators whose fundamental resonance frequency depends on the thickness of the ferroelectric/piezoelectric thin film. As a result, fabrication of multiple frequency thickness mode resonators on a single wafer requires many different deposition and chemical etching cycles. Therefore, integration of multiple frequency resonators is not economical due to their high fabrication costs. Furthermore, precise frequency control of these resonators requires very uniform film thicknesses. This requirement is even more stringent for SMRs.

In contrast to thickness mode resonators, the fundamental resonance frequency of contour mode resonators is determined by their lateral dimensions. Therefore, the fundamental resonance frequency of contour-mode resonators can be precisely controlled with standard lithographic technologies. In [10], contour mode resonators have been demonstrated using AlN thin films. Contour mode resonators are reported to have a wafer thickness uniformity tolerance which is 10 times larger than that of thickness mode resonators. By combining the advantages of contour mode devices together with the advantages of ferroelectric thin films, many of the shortcomings of current resonator and filter technologies can potentially be overcome.

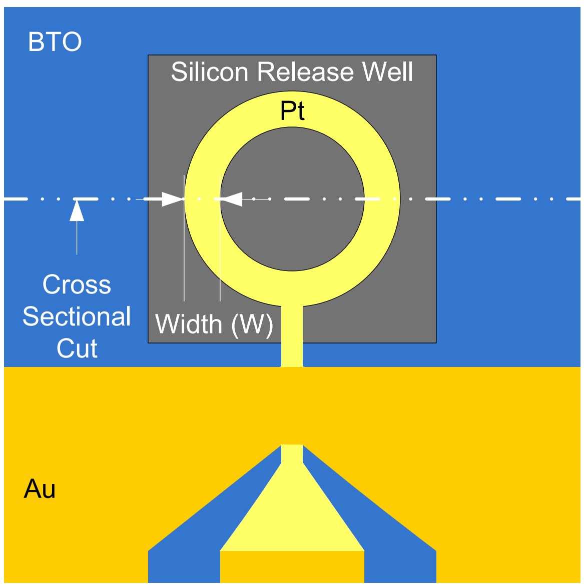
In this paper, an intrinsically switchable contour mode resonator is demonstrated for the first time. Because of the electrostrictive effect, ferroelectric thin film contour mode resonators can be turned on and off by the application of a DC bias voltage. This technology simplifies the fabrication of switchable resonators. Integration of a number of such resonators with different resonant frequencies onto a single wafer would enable the realization of intrinsically switchable resonators and filter banks with reduced complexity, power consumption, size, and cost.

II. Design

A BTO contour mode resonator consisting of a BTO thin film that is sandwiched between two platinum electrodes is designed. The cross sectional view of the resonator is shown in Fig. 1 (a).



(a)



(b)

Fig. 1. (a) Cross sectional and (b) top view of the switchable BTO thin film contour mode circular-ring resonator.

The proposed switchable contour mode resonator has a circular-ring structure as shown in Fig. 1(b). The resonator can be electrically represented by the modified Butterworth-Van Dyke circuit model shown in Fig. 2. This model illustrates the series and parallel resonance frequency of the resonator. The fundamental series resonant frequency is determined by the properties of the thin film and the width of the ring as indicated in (1)

$$f_s \approx \frac{1}{2W}\sqrt{\frac{E_P}{\rho(1-\sigma^2)}} \tag{1}$$

where W is the width of the ring resonator, ρ is the mass density, σ is the in-plane Poisson's ratio, and E_P is the equivalent Young's modulus of the BTO thin film [10]. The ring width is 10 µm in this demonstration, corresponding to a calculated series resonance frequency of 178 MHz. Note that neither the mass loading effect due to the Pt electrodes nor the tether anchor effect is taken into account in equation (1) for the calculation of the fundamental series resonance frequency f_s.

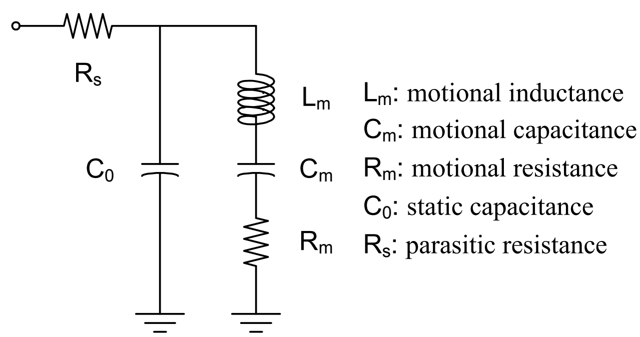


Fig. 2. Modified Butterworth-Van Dyke circuit model for acoustic wave resonators.

TABLE I
MATERIAL PROPERTIES OF BTO [11]

	ρ (kg/m^3)	σ	E_P (GPa)
BTO	5800	0.3	67

III. FABRICATION

The BTO switchable contour mode resonator is fabricated on a high resistivity silicon substrate (5000 Ω·cm) with a thickness of 525 µm. A layer of thermal SiO_2 is deposited on top of the substrate. On top of the SiO_2, a 100 nm platinum bottom electrode is patterned by e-beam evaporation and liftoff. A 405 nm BTO thin film is then deposited by pulsed laser deposition (PLD) using the conditions described in [7]. The top electrode is deposited using the identical procedure as for the bottom electrode. A silicon release window is opened by wet etching of the BTO and SiO_2 layers. Then 500 nm of gold is deposited for the CPW probe pads. Finally the device is released by an isotropic silicon dry etching process using XeF_2. The released resonator is shown in Fig. 3.

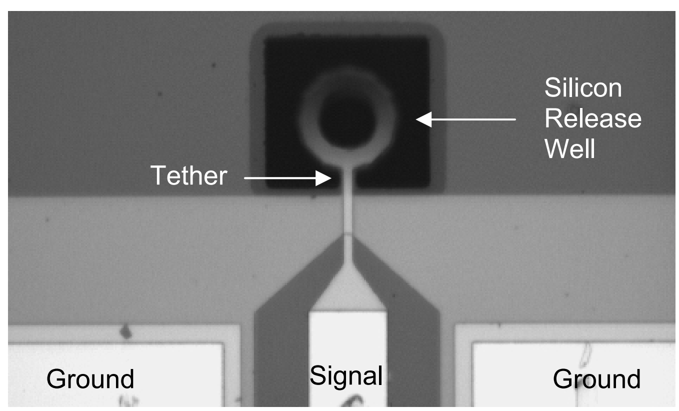


Fig. 3. Micrograph of the released switchable BTO thin film contour mode circular-ring resonator. The bending of the resonator structure causes the section away from the tether to be out of focus.

IV. Measurement Results

The fabricated contour mode resonator is characterized using an Agilent E8364B vector network analyzer and a GGB ground-signal-ground (GSG) probe with a pitch size of 150 µm. The input impedance of the resonator, Z_{in}, is measured as the DC bias voltage is gradually increased from 0 V to 12 V. At 12 V DC bias, the resonator exhibits a series resonance frequency f_s of 159.7 MHz and a parallel resonance frequency f_p of 160.45 MHz as can be seen in Fig. 4 (a). The quality factors are calculated to be 47 and 83 for the series and parallel resonance frequencies, respectively, using (2) where $d\phi_{Zin}/df$ is the change in the phase of the input impedance with respect to frequency. At a 1 V DC bias, the resonance is turned off, as shown in Fig. 4 (b). In the absence of DC bias, a weak resonance at 158 MHz is observed, also shown in Fig. 4 (b).

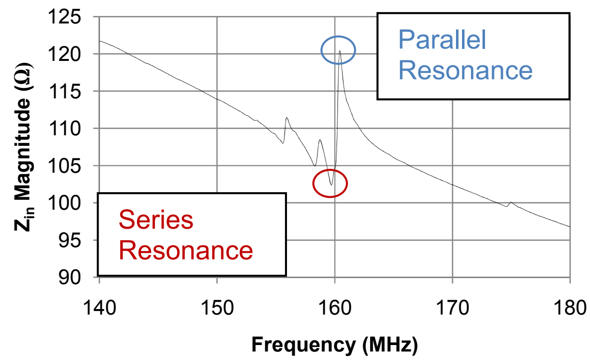
The change in resonance behavior of the BTO resonator at different DC bias is attributable to change in polarization of the BTO thin film. At high DC bias, the polarization leads to an enhanced piezoelectric response. At low DC bias, e.g. 1 V, the piezoelectric response is off. In the absence of DC bias, the spontaneous polarization of the BTO results in a weak resonance.

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

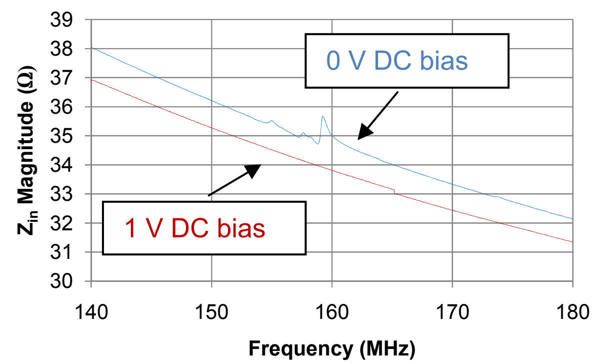
$$K_t^2 = \frac{\pi}{2}\frac{f_s}{f_p}\tan\left(\frac{\pi}{2}\frac{(f_p - f_s)}{f_p}\right) \tag{3}$$

The effective electromechanical coupling coefficient of the BTO thin film resonator is calculated to be 1.15% using (3). This value is comparable to that of contour mode resonators using piezoelectric AlN thin films [10].

Both the series and the parallel resonance frequencies increase monotonically with the DC bias voltage as shown in Fig. 5. As expected, the bias does not significantly change the resonance frequency, exhibiting a tuning range of only 0.8%. This value is comparable to thickness mode SMRs using ferroelectric thin films [8].



(a)



(b)

Fig. 4. Plot of the input impedance of the BTO thin film contour mode resonator with (a) 12 V DC bias and (b) 0 V and 1 V DC bias.

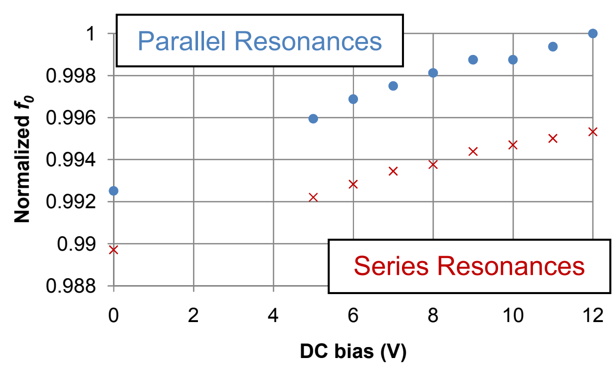


Fig. 5. Plot of normalized resonance frequencies versus applied DC bias of the BTO thin film contour mode resonator.

V. Conclusion

A DC electric field switchable contour mode resonator using ferroelectric BTO thin films is demonstrated for the first time. The fundamental series resonance frequency of the contour mode resonator is determined by its lateral dimensions. The BTO thin film contour mode resonator can be turned on by the application of a DC bias voltage. This technology enables the fabrication of intrinsically switchable resonator and filter banks on a single wafer.

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