Intrinsically Switchable Ferroelectric BAW Resonators and Filters

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***Abstract*— In this paper, intrinsically switchable radio frequency (RF) resonators and bandpass filters using ferroelectric thin film technology are presented. Ferroelectrics materials exhibit electrostriction and dc electric field induced piezoelectricity. This paper discusses the design and fabrication of intrinsically switchable film bulk acoustic resonators (FBARs), FBAR filters, and contour mode resonators by employing the dc electric field induced piezoelectricity of the ferroelectric $Ba_xSr_{(1-x)}TiO_3$. Such resonators and filters have the ability to decrease the complexity, power consumption, and cost of frequency agile radios while improving their performance and reliability.**

I. Introduction

Future wireless communication systems will rely more and more on frequency agility for better spectrum utilization. Frequency controlling components such as resonators and filters have an enormous impact on the overall design of frequency agile wireless communication systems. Current reconfigurable radios require the use of many fixed frequency circuit components. Each frequency band requires its own dedicated RF frontend, which needs to be switched in and out of the circuit by using solid state switches. Intrinsically switchable ferroelectric resonators and filters can significantly simplify the design of reconfigurable radios.

Ferroelectric thin films have a dc electric field dependent piezoelectric response. By utilizing bulk acoustic wave (BAW) filter banks based on ferroelectric thin films in radios, the desired frequency spectrum can be selected by applying a bias voltage to a one of the filters. Ferroelectric based resonators also have many other advantages. For example, the ferroelectric $Ba_xSr_{(1-x)}TiO_3$ exhibits a higher electromechanical coupling coefficient than the traditional AlN used in BAWs [1][2]. This can lead to lower insertion losses and larger bandwidths in bandpass filters. These devices can also be made to have a much smaller footprint due to their higher permittivity. Ferroelectric thin films are also used to design varactors and digital memories. One can envision that future frequency agile radios will utilize ferroelectric thin film technology for many of their components, increasing the degree of integration and decreasing costs.

In this paper, the concept of intrinsically switchable resonators and filters is presented. Through the integration of many ferroelectric resonators and filters on a single wafer, multi-frequency radio design can be significantly simplified (Fig. 1).

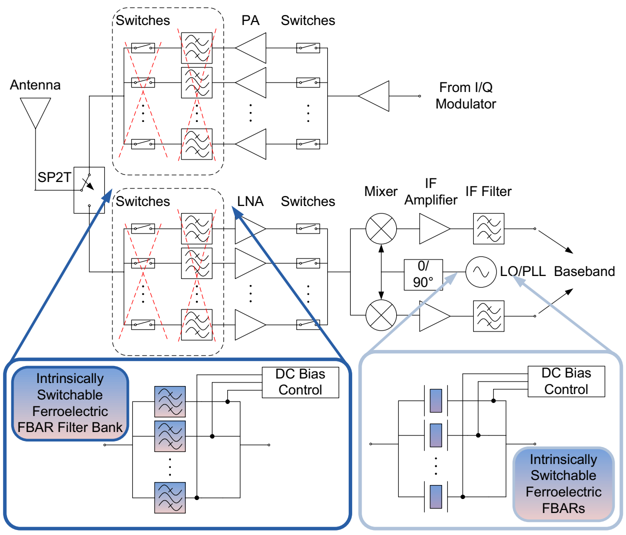

Fig 1. Block diagram of a frequency agile transceiver illustrating the application of ferroelectric thin film devices in frequency agile radios.

II. Intrinsically Switchable Film Bulk Acoustic Wave Resonators

A. Theory and Design

The cross section of a ferroelectric FBAR is shown in Fig. 2. Ferroelectric FBARs are similar to traditional FBARs. Both consist of a dielectric material that is sandwiched between two electrodes and have the substrate below the device etched away, leaving a floating membrane. The key difference is that ferroelectric FBARs utilize a ferroelectric, rather than piezoelectric, thin film as the dielectric. This enables the resonators to be intrinsically switchable.

The series resonance frequency of an FBAR is determined by the thickness of parallel plate structure and can be calculated by using the acoustic wave transmission line model [3]. The frequency response of an FBAR can be represented by the modified Butterworth-Van Dyke (MBVD) equivalent circuit model, which is shown in Fig. 3 [4].

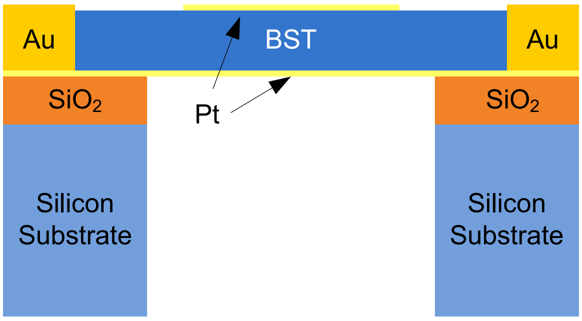

Fig 2. Cross section of a ferroelectric film bulk acoustic wave resonator (FBAR). By using the ferroelectric $Ba_{0.5}Sr_{0.5}TiO_3$ (BST), the resonator can be turned on and off with the application of a dc bias.

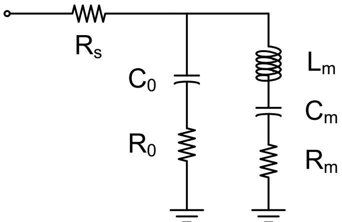

Fig 3. The modified Butterworth-Van Dyke model (MBVD), which is one of the equivalent circuit models for BAW resonators.

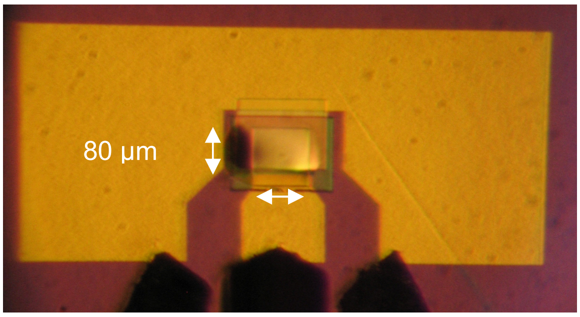

Fig 4. Micrograph of a BST FBAR that has dimensions of 80 µm × 80 µm.

B. Fabrication

The ferroelectric FBARs are fabricated on high resistivity silicon substrates. A layer of SiO_2 is thermally grown on top of the silicon. A 100 nm platinum bottom electrode is patterned by e-beam evaporation and liftoff. The SiO_2 is etched for creating silicon release windows. A layer of $Ba_xSr_{(1-x)}TiO_3$ (BST) thin film is then deposited by pulsed laser deposition (PLD) using an excimer laser (λ = 248 nm, 25 ns pulse width, ~1.75J/cm^2) with a substrate temperature of 650 °C in a 300 mTorr oxygen environment. The top electrode is deposited using the identical procedure as for the bottom electrode. The BST is then selectively etched to complete the silicon release windows. A gold contact layer is then deposited to serve as the co-planar waveguide and probe pads. The devices are released by using either XeF_2 or deep reactive ion etching to etch away the silicon supporting the parallel plate structure, resulting in a membrane. A Micrograph of a BST FBAR is shown in Fig. 4.

C. Measurement Results

Measurements of the BST FBARs were performed on a Cascade Microtech probe station using 150 µm ground-signal-ground probes connected to an Agilent E8364B vector network analyzer. S-parameters were recorded over a wide range of frequencies for various bias voltages, which are applied through a bias tee. The quality factor and effective electromechanical coupling coefficient of the resonators are calculated by (1) and (2).

$$Q = \frac{f}{2}\frac{d\phi_{Zin}}{df}\bigg|_{f=f_s,f_p} \quad (1)$$

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

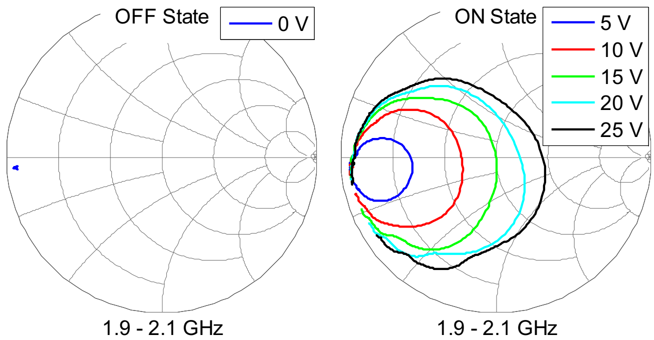

Fig 5. Response of a $Ba_{0.5}Sr_{0.5}TiO_3$ FBAR at various bias voltages.

BST FBARs do not show any resonance in the absence of a dc bias. When a bias voltage is applied, the resonators turn on and the resonance grows stronger with larger voltages, as shown in Fig. 5. For the FBAR presented in Fig. 5, at 25 V dc bias, the resonator has a series and parallel resonance at 1.975 and 2.035 GHz with corresponding quality factors of 233 and 218. The electromechanical coupling coefficient is calculated to be 7.07 % [5].

III. Intrinsically Switchable FBAR Filters

A. Theory and Design

By connecting several BAW resonators together, RF bandpass filters can be designed. Here, the results for an intrinsically switchable 1.5 stage ladder filter based on ferroelectric FBARs are presented. The filter consists of two series FBARs and two shunt FBARs, as shown in Fig 6. The resonance frequencies of the shunt FBARs are slightly reduced by thickening the top electrode. In this design, low frequency signals see a short to ground due to the series resonance of the shunt FBAR and high frequency signals see an open due to the parallel resonance of the series FBAR, as shown in Fig. 7. A dc bias can be applied to the center node of the filter while all other nodes are held at dc ground. The fabrication procedures for FBAR filters are the same as for the individual FBAR except for an additional step that consists of sputtering a layer of high resistivity SiCr for creating dc biasing lines. A micrograph of a FBAR filter is shown in Fig. 8.

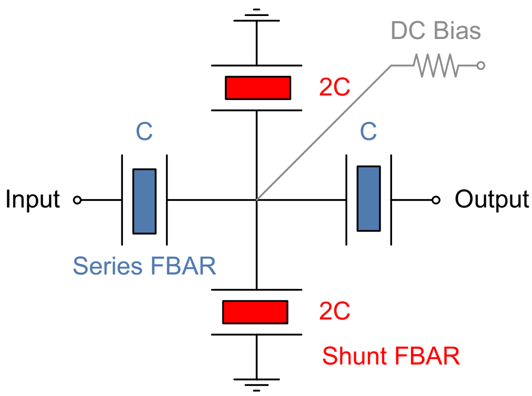

Fig 6. Schematic of the 1.5 stage ladder filter. The capacitance of the each shunt FBAR is twice that of each series FBAR.

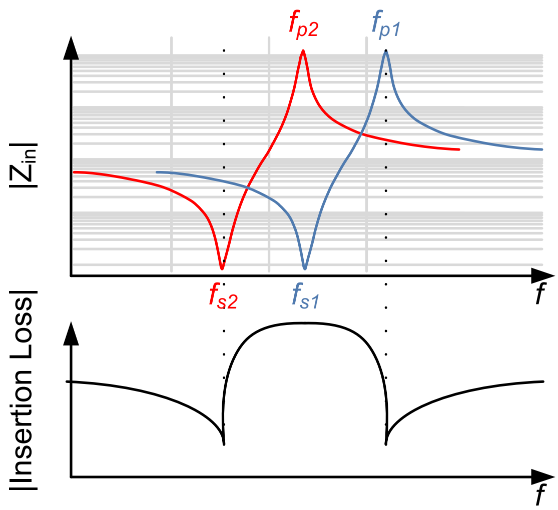

Fig. 7. Operation principle of BAW bandpass filters.

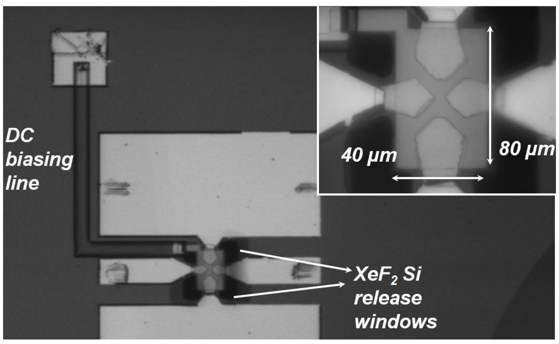

Fig 8. Micrograph of a $BaTiO_3$ (BTO) FBAR filter that has dimensions of 40 μm × 80 μm.

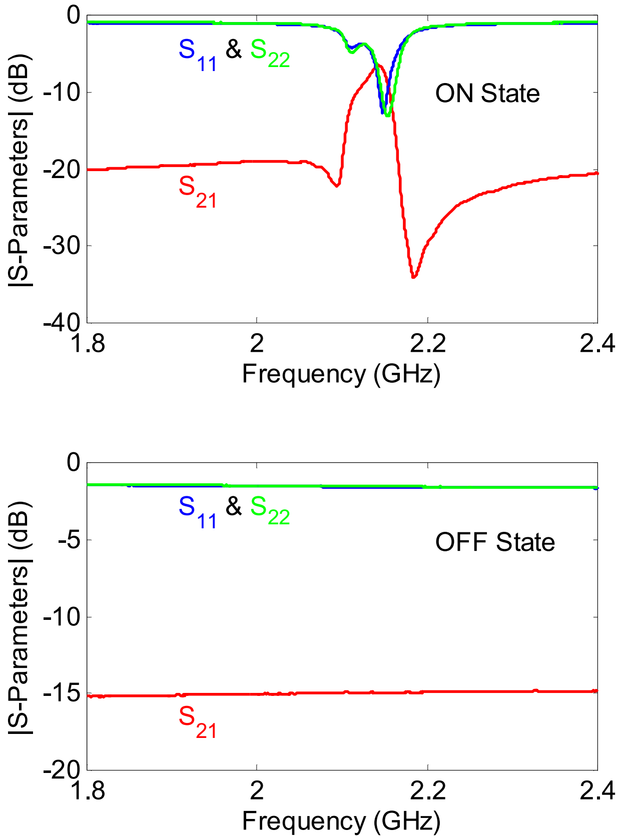

Fig 9. Response of a BTO FBAR filter in the on and off state.

B. *Measurement Results*

The $BaTiO_3$ (BTO) ferroelectric FBAR filter presented here provides a 15 dB insertion loss with the absence of a dc bias voltage. With the application of a 15 V dc bias, a bandpass response at 2.14 GHz is observed with a 3 dB bandwidth of 40 MHz. The filter's insertion loss in the passband is 6.2 dB, the return losses for both ports are greater than 10 dB, and the out-of-band rejection is 20 dB (Fig. 9) [6].

IV. Intrinsically Switchable Contour Mode Resonators

A. *Theory and Design*

Contour mode resonators are a type of BAW which have a resonance frequency determined by the lateral dimension of the structure as opposed to its thickness. Here the design of a contour mode resonator that has a circular-ring structure is described. The series resonance frequency for the structure is dependent upon the width of the ring and the acoustic properties of the materials and can be approximated by (3).

$$f_s \approx \frac{1}{2W}\sqrt{\frac{E_P}{\rho(1-\sigma^2)}} \quad (3)$$

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 thin film [7]. The fabrication procedures for the ferroelectric based contour mode resonators are the same as for the FBAR. A micrograph of a ferroelectric contour mode resonator is shown in Fig. 10.

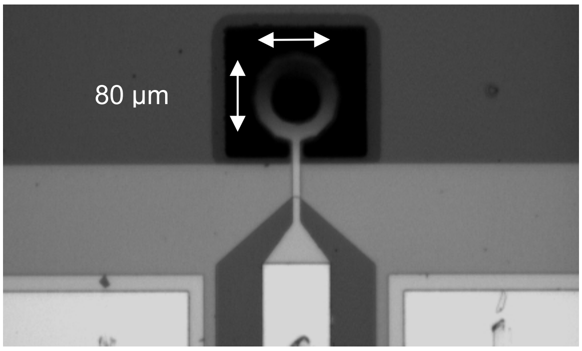

Fig 10. Micrograph of a circular ring-shaped contour mode resonator.

B. *Measurement Results*

Again with the application of a dc bias voltage, circular ring-shaped contour mode resonators are turned on. The resonator presented here has a series and parallel resonance at 159.7 and 160.5 MHz with corresponding quality factors of 47 and 83 at a bias voltage of 12 V as shown in Fig 11. The resonance is switched off with a bias voltage of 1 V. The effective electromechanical coupling coefficient is 1.15 % [8]. The work presented here is the first demonstration of a ferroelectric contour mode resonator. The advantage of using contour mode resonators is ability to lithographically define the resonance frequency, enabling the fabrication resonators and bandpass filters of all different frequencies on a single wafer. Additional work on contour mode resonators, which utilize interdigitated electrodes, has also been done. Intrinsically switchable interdigitated contour mode resonators which have a resonance frequency up to 1.67 GHz have been demonstrated [9].

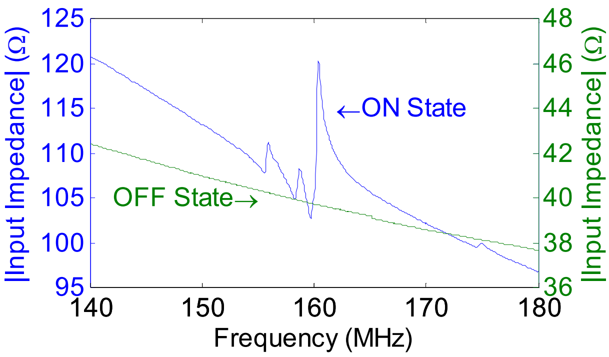

Fig 11. Frequency response of a BTO circular ring-shaped resonator at 1 V (OFF State) and 12 V dc bias (ON State).

V. Conclusions

Ferroelectric thin films have been demonstrated in FBARs, FBAR filters, and contour mode resonators. They enjoy the advantages of bulk acoustic wave (BAW) technology and have the additional property of being intrinsically switchable. The performance of these devices is expected to improve as techniques for growing ferroelectric thin films matures.

Acknowledgment

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