Strontium Titanate DC Electric Field Switchable and Tunable Bulk Acoustic Wave Solidly Mounted Resonator

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Abstract — A voltage switchable/tunable strontium titanate solidly mounted BAW resonator was implemented using an acoustical Bragg reflector of alternating high and low acoustic impedance layers. In the absence of any bias the device is merely capacitive, but under a DC bias the material becomes piezoelectrically active, leading to a BAW resonance that is effectively turned on and off by the applied field. In the resonant state a voltage-dependent frequency trimming of 1 % is observed, from 7.05 GHz to 6.98 GHz with an applied bias of 0–9 V, respectively. The quality factor at the resonant frequency was approximately 100, limited by the simplicity of the device design. The Q was relatively constant with applied bias, with an effective electromechanical coupling coefficient that varied linearly with applied bias up to a maximum of 3.3 %.

Index Terms — Acoustic resonators, bulk acoustic wave devices, delay filters, ferroelectric films, piezoelectric resonators.

I. INTRODUCTION

Strontium titanate (STO) and barium strontium titanate (BST) are known to have a voltage-dependent dielectric constant [1], and this property has been investigated for many years for potential use in adaptive and frequency-agile RF components [2]. In recent years it has been demonstrated that these materials also have an electrostrictive property [3, 4] that can be exploited to realize voltage-switchable bulk-acoustic wave (BAW) devices for RF applications [5, 6, 7]. Using this property, high-Q and voltage-activated filters and/or switches can be created in the microwave frequency range.

Unlike conventional BAW technology, the piezoelectric coupling coefficient in STO- and BST-based resonators is controlled by an applied DC field. In the absence of a DC field, the piezoelectric coupling is negligible; at fields approaching 0.7 MV/cm DC field, piezoelectric coupling constants as high as 10% have been measured on thick BST films. This new technology may allow for a new class of voltage-selectable high-Q/low-loss filter banks, addressing a critical need in modern RF/microwave/mm-wave communication systems.

To achieve high Q-factors, the resonator must be mechanically isolated from the damping effects of the substrate. In modern BAW devices this is typically done using either a suspended membrane approach (film-bulk-acoustic resonators, or FBAR), or an acoustic Bragg reflector (solidly-mounted resonator, or SMR). In this paper we demonstrate an SMR type resonator on sapphire, using a relatively simple four-layer mirror structure of Pt-SiO₂.

II. DESIGN AND FABRICATION

A properly designed acoustical Bragg reflector for the SMR structure consists of multiple quarter wavelength layers of alternating high and low acoustic impedance. In this work, platinum and silicon dioxide were used. The quarter wavelength and acoustic impedance are determined by [8].

Fig. 1. (a) Schematic diagram of SMR, (b) SEM cross section of SMR device.
schematic representation of the device showing the substrate, acoustic mirror and contact points, Figure 1 (b) is an SEM cross section of the image of the device. Tabulated in Table 1 are the material parameters used in the design of the SMR device.

### Table 1. Material acoustic parameters at RT.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Density (Kg/m$^3$)</th>
<th>Longitudinal Elastic Constant (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,3,5,7</td>
<td>Pt</td>
<td>21500</td>
<td>346.7</td>
</tr>
<tr>
<td>2</td>
<td>SrTiO$_3$</td>
<td>5123</td>
<td>348.17</td>
</tr>
<tr>
<td>4,6</td>
<td>SiO$_2$</td>
<td>2649</td>
<td>105.75</td>
</tr>
</tbody>
</table>


bottom electrode of our solidly mounted resonator (SMR) structure. The platinum and the silicon dioxide were deposited by electro-beam evaporation and plasma enhanced chemical vapor deposition, respectively. The strontium titanate (STO) layer (60 nm) was deposited by radio frequency magnetron sputtering from a stoichiometric SrTiO$_3$ target, on top of the acoustical Bragg reflector structure. The STO deposition parameters are described in other publications [9, 10]. The SMR Structure was fabricated using standard processing techniques such as photolithography, chemical wet etching, and lift-off for the top electrode. Figure 1 (a) is a

### III. EXPERIMENTAL RESULTS

The one port S-parameter data for the SMR structure was measured using a Cascade Microtech probe station, GGB GSG probes and an E8361A vector network analyzer. Figure 2 and Figure 3 show the tunability and switchability of the SMR structure, respectively. Figure 2 the resonator is tunable from 7.05 GHz at 1 VDC to 6.98 GHz at 9.0 VDC. The dc bias was varied from 0 V to 9.0 V in steps of 1 V.

Fitting the collected data to the modified Butterworth-Van Dyke (MBVD) [11,13] model the quality factor of the resonator was calculated (1) to be 101 over the bias range (Fig. 4).

$$Q = \frac{\omega}{R_m}$$

(1)

$$k_{\text{eff}}^2 = \frac{\pi^2}{4} \frac{f_a - f_r}{f_a}$$

(2)

where $\omega_r$ is the resonant frequency, $L_m$ is the motional inductance, $R_m$ is the motional resistance, and $f_r$ and $f_a$ are the resonance and antiresonance frequencies, respectively. The return loss at 9.0 V was -9.5 dB. The effective electromechanical coupling coefficient ($k_{\text{eff}}^2$) was extracted from the MBVD parameters to be 3.3 % and near linear, as can be seen from Figure 4. The measured resonant frequency was normalized to the maximum measured frequency at 1V dc and plotted in Figure 5 against the applied dc voltage. From Figure 5 we can see that the frequency is decreasing as a function of increasing applied dc voltage.

![Fig. 2. Return loss of tunable SMR showing the tunability and the inset is a plot of the main resonance over a wide frequency range.](image1)

![Fig. 3. Plot of the return loss of switchable STO SMR, showing the off state in red and on state in blue.](image2)

![Fig. 4. Plot of the resonator quality factor (blue diamonds) and the electromechanical coupling coefficient (red circles) vs applied dc voltage.](image3)
IV. DISCUSSION

Note that the low resonance frequency of our device with respect to the half-wavelength resonance frequency of the STO layer alone (~70 GHz), is due to the thick metal electrodes that are in the acoustical path of the resonator [12]. In future designs, thicker STO or BST films and thinner electrodes would be used instead, since the thick metal electrodes have a damping effect on the Q-factor. The thin STO film used in this work was chosen merely for simpler comparison of the device results with earlier varactor structures of similar design, but without the mirror structure [7].

Nevertheless, this work (Fig. 3 in particular) demonstrates the potential for voltage-switchable resonators. Using Agilent’s ADS software, the one-port reflection coefficient data was fit to an MBVD model, and using this model we can then predict the behavior of the structures in other circuit topologies. A simple example is the capacitively coupled shunt resonator transmission-structure in Figure 6. In Figure 7 the simulated insertion loss at 7 GHz is -6.5 dB.

In addition to the excessively thick electrodes and relatively thin STO layer, two other Q-limiting factors can be easily identified in this work: the use of only four layers in our Bragg mirror, and our use of a direct probe measurement on the top electrode of the device. Future devices would use a larger number of mirror layers, and would move the measurement contacts away from the device, with electrical contact via a thin cross-over metal. In addition, higher piezoelectric coupling coefficients can be obtained by using BST films instead of STO. Devices using these advances are currently in development.

V. CONCLUSION

In conclusion, a dc electric field tunable and switchable STO solidly mounted bulk acoustic wave resonator has been demonstrated. The return loss at 9.0 volts is -9.5 dB; the quality factor is 101 and $k_{eff}^2$ is 3.3 % at a bias voltage of 9.0 V. With further advances in the device design, this technology could allow for the creation of high-Q switchable filters for RF/microwave front-ends.

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REFERENCES


