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Original Article

Design and Modelling of Solidly-Mounted Resonators using BaTiO3

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Abstract - *Solidly-Mounted Resonators (SMRs) are crucial in applications involving Radio Frequency (RF) and acoustic waves. Because they offer high-performance filtering and frequency control capabilities, the primary focus of this work is the design and simulation of SMRs using Barium Titanate ($BaTiO_3$) as the piezoelectric material. $BaTiO_3$ is a potential replacement for more conventional materials like ZnO and AlN because of its better electromechanical coupling and dielectric properties. The quality factor, frequency response, and acoustic wave propagation characteristics of the resonator are investigated in the study using Finite Element Modeling (FEM). A multi-layer acoustic Bragg reflector enhances acoustic wave confinement, lowers energy loss, and boosts device efficiency. The study also looks into how $BaTiO_3$-based SMRs are suitable for next-generation RF filters and sensing applications due to their improved resonance characteristics and higher coupling coefficients. The results offer a means to optimize SMR architectures for improved integration with modern sensing and communication technologies.*

Keywords - *Solidly Mounted Resonator (SMR), Quality factor, Bragg reflectors, Filter topology, Bulk Acoustic Wave (BAW).*

1. Introduction

RF electro-acoustic resonators and filters are essential elements for wireless communication equipment. The forthcoming generation of mobile systems needs a stringent reduction in component size, elevated operation frequency, and enhanced power resilience. Consequently, BAW devices have arisen as an effective alternative to conventional filtering systems. Solidly Mounted Resonators (SMRs) are one of the critical components in the ever-changing world of mobile, with applications ranging from sensing to filtering. As the desire for improved performance and functionality grows, there is an urgent need to go beyond surface-level understanding and investigate the complexities of SMRs.

Currently, the designated frequency spectrum for growing wireless telecommunications systems ranges from 500 MHz to 6 GHz [1], and the array of functionalities offered by these systems, including audio data and image processing, is consistently expanding It takes a lot of space to integrate these systems and necessitates the utmost downsizing of RF active and passive electrical components. This paper discusses a particular kind of Bulk Acoustic Wave (BAW) resonator that is currently widely used in RF filter construction, facilitating the separation of information from a congested spectrum. Recently, RF-Filters utilizing SMR have been identified as a viable alternative to traditional lumped LC components, dielectric ceramics and Surface Acoustic Wave (SAW) resonators. BAW technology seems to excel compared to others in terms of compactness, performance, and potential for on-chip integration [2].

2. Bulk Acoustic Wave (BAW) Resonator

The BAW resonator constitutes the fundamental component of BAW technology [3]. It is a piezoelectric device, indicating that the piezoelectric effect facilitates electromechanical conversion. BAW resonators have become prevalent in filters but can also be utilized in other applications, including sensors [4] and oscillators [5]. Figure 1 illustrates that a BAW resonator functions geometrically as a capacitor; an acoustic wave is formed when a voltage differential is applied to the electrode. The primary mode of the BAW resonator is the thickness or longitudinal mode. The bulk acoustic wave reflects off the extensive plate surfaces, with resonance induced by wave excitation in the thickness direction. The resonance frequency is dictated by the thickness and characteristics of the piezoelectric layers and the electrode. In the case of more intricate resonators, any further layer will influence the resonator. At the fundamental resonance, the resonator plates contain only one half of an acoustic wavelength.

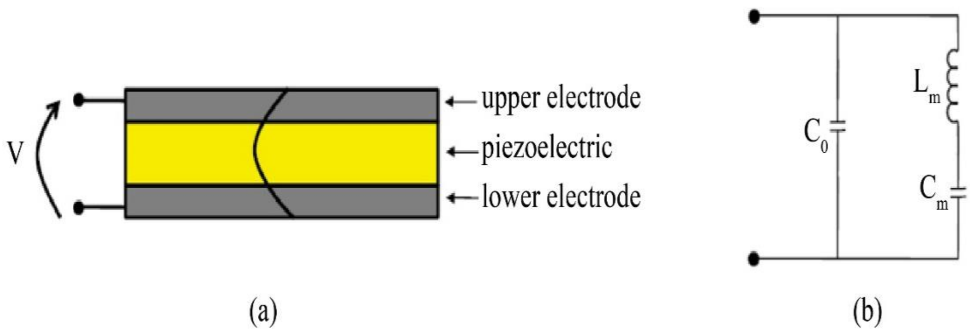

Fig. 1(a)Cross section of BAW resonator, and (b)Electrical equivalent model of BAW resonator, the BVD model.

3. Process Design

Figure 2(a) presents a schematic representation of the SMR cross section. A 3D Model of the Solidly Mounted Resonator in COMSOL Multiphysics is shown in Figure 2(b). The examined devices consist of a thin film of piezoelectric material interposed between two metallic electrodes, with the lower electrode placed on an acoustic isolator [6]. An air cavity can be used to accomplish this [7]. However, a Bragg mirror stops acoustic leakage into the silicon substrate in the case of SMR [8]. In contrast to Air-Gap type (AGR) Resonators, these Bragg mirrors increase durability for subsequent chip-dicing processes [9]. Although SMR exhibits better power handling and temperature stability, it experiences acoustic energy losses in the Bragg mirrors. On the other hand, AGR effectively limits acoustic energy, producing better quality features.

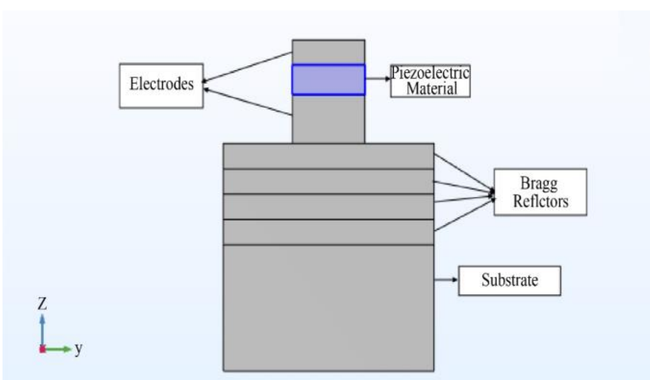

Fig. 2(a) schematic presentation of SMR cross section

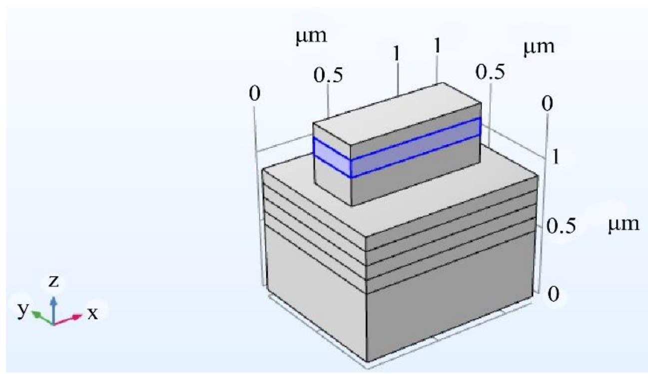

Fig. 2(b) 3D Model of the solidly mounted resonator in COMSOL multiphysics

[10, 11] BaTiO3 is a good option for filtering applications because it is a piezoelectric thin film material with superior electromechanical coupling, high thermal conductivity, RF-IC chemical compatibility, and low processing temperature, making above-IC integration easier.Because of its suitable acoustic impedance, aluminium (Al) is frequently used for the top and bottom electrodes. The BaTiO3 layer's thickness primarily determines the antiresonance frequency, which decreases with increasing thickness. This study examines a 0.14 µm-thick BaTiO3 film, with aluminium utilized for the top and bottom layers measuring 0.1 µm and 0.2 µm, respectively. With a specific resonance frequency of 5 GHz, the Bragg mirrors are made up of a sequence of quarter-wavelength (λ/4) layers [12-14] of high and low acoustic impedance materials (W and SiO2, respectively). Table 1. shows the details about the dimensions of SMR.

Table 1. Design parameters of SMR

Material		**Length (L)**	**Width (W)**	**Thickness**					**Frequency (GHz)**	**Quality Factor**
Piezo	Brag			Si	Brag Layers	Bottom Electrode	piezo	Top Electrode		
BaTiO3	SiO2/W	1.1	0.35	0.5	0.1	0.2	0.14	0.1	5.6 G Hz	1780

As shown in Figure 2(a), the Solidly Mounted Resonator consists of four major components: Electrodes, Piezoelectric material, Bragg reflectors, and Substrate. To create a detailed 3D model of the Solidly Mounted Resonator (SMR) in COMSOL Multiphysics, each component's geometry and dimensions must be accurately represented. Starting with piezoelectric materials used for the experimentation process, the area is defined as 1.1 µm * 0.35 µm, with a specified thickness of 140 nm. Similar areas for the aluminium (Al) electrodes are considered: 1.1 µm * 0.35 µm for the electrode below the piezoelectric finger and the electrode above the piezoelectric material, with respective thicknesses of 100 nm and 200 nm. The Bragg reflectors are made of tungsten (W), with a thickness of 100 nm. The 100 nm-thick silicon dioxide (SiO_2) layer and the 500 nm-thick silicon (Si) substrate are comparable. These dimensions are the basis for building the geometry in COMSOL Multiphysics, guaranteeing an accurate depiction of the SMR's constituent parts.

The 3D Model will enable thorough simulations to examine the behavior and performance characteristics of the SMR by precisely describing the dimensions and attributes of each component material. Figure 2(b) shows how the Model was built in COMSOL Multiphysics, highlighting the piezoelectric material. The Quality Factor vs. Resonating Frequency graph is shown in Figure 3(a), and the Admittance vs. Resonant Frequency graph is shown in Figure 3(b).

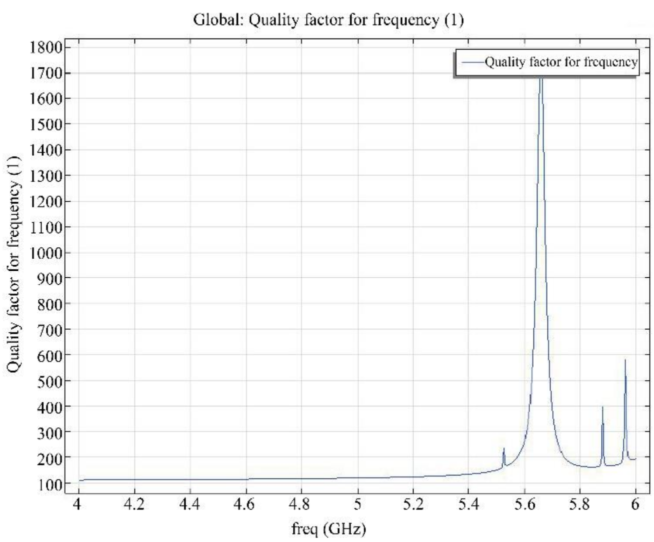

Fig. 3(a) Quality factor Vs Frequency

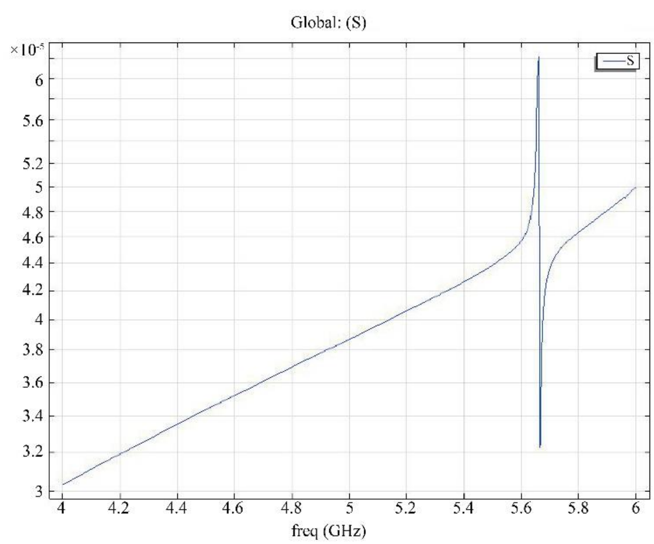

Fig. 3(b) Admittance vs Frequency

4. Electrical Equivalent of a BAW Resonator

The popular equivalent circuit model for Bulk Acoustic Wave (BAW) resonators is the Butterworth-Van Dyke (BVD) model [15, 16]. It is made up of a parallel plate capacitance (Co), a motional arm made up of a motional inductance (Lm), motional capacitance (Cm), and motional resistance (Rm) as shown in Figure 4(a). The motional arm represents the resonator's mechanical and electrical properties, while the parallel plate capacitance represents the electrical capacitance between the electrodes.

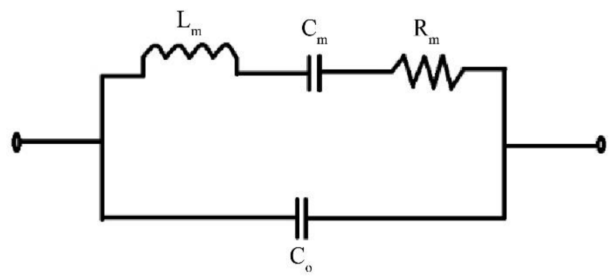

Fig. 4(a) BVD Model of Resonator

A measurement of the resonator's inertia, the motional inductance (Lm), is correlated with its mass. The motional capacitance (Cm), which is connected to the resonator's compliance, is a measure of the elasticity of the resonator. The motional resistance (Rm), which is connected with the resonator's quality factor (Q), is a measure of energy loss in the resonator. Performance metrics for the resonator, such as the quality factor (Q) and coupling coefficient (k2), can be extracted using the BVD model. The BVD circuit elements can be used to calculate the ratio of energy lost to energy stored, which is known as the quality factor (Q), on various loss mechanisms given as:

$$Q = \frac{\omega_0 L_m}{R_m} \quad (1)$$

Where ω0 is the resonance frequency.

The BVD model is simulated in the ADS tool as shown in Figure 4(b).

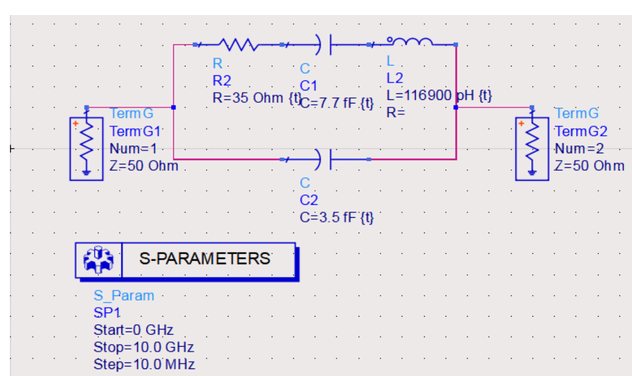

Fig. 4(b) BVD model of resonator

Table 2. BVD model extracted parameters

Parameter	value
Co (fF)	3.5
Cm (fF)	7.7
Lm (pH)	116900
Rm (Ω)	35
Q	1780
fs (GHz)	5.64
fp (GHz)	5.68

5. Filter Topologies

T-type structures offer high impedance at both input ends and are suitable for specific applications, including switching conversion circuits. However, their limited use in certain scenarios and increased complexity make them less versatile.

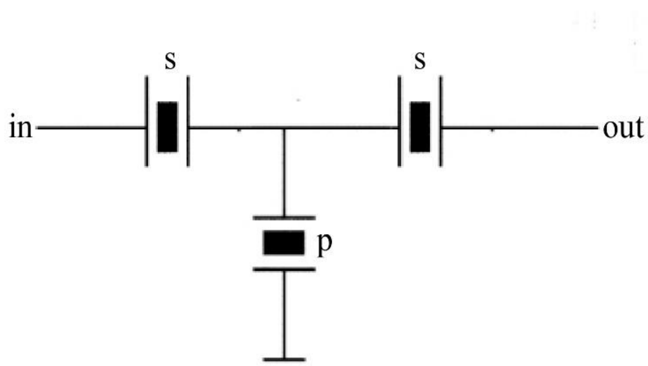

Fig. 5(a) T-type structure

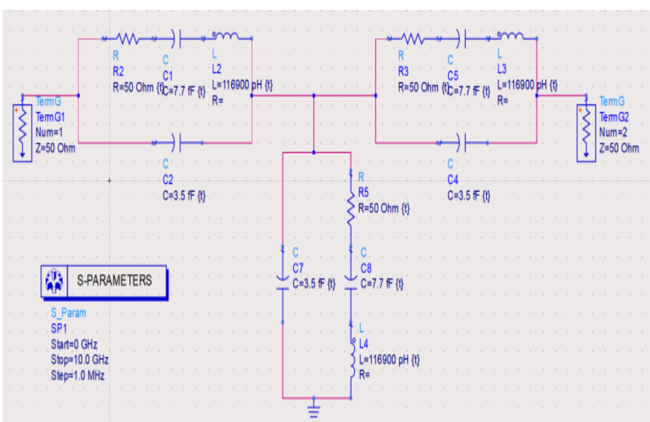

Fig. 5(b) ADS tool T-type connection of resonators

This paper discusses the electrical equivalent of a BAW resonator using the S parameter model (BVD model) and T topology of a filter. The study aims to improve knowledge of BAW resonator and filter design and optimization for communication systems.

6. Result and Discussion

- Resonance Performance - The simulation results indicate that $BaTiO_3$-based Solidly-Mounted Resonators (SMRs) achieve a higher electromechanical coupling coefficient (k^2_eff) compared to conventional AlN and ZnO-based SMRs.
- Frequency Response - The resonators exhibit sharp resonance peaks, demonstrating efficient energy trapping and minimal signal loss. The resonance frequency and antiresonance frequency are well-defined, ensuring optimal filtering performance in RF applications.
- Quality Factor (Q-Factor) - The Q-factor analysis shows that $BaTiO_3$-based SMRs maintain high-quality resonance characteristics, with reduced acoustic losses due to optimized Bragg reflector design.
- Bragg Reflector Efficiency - Multi-layer acoustic reflectors significantly improve wave confinement, reducing substrate leakage and enhancing the overall device efficiency.
- Material Influence- $BaTiO_3$ is a good substitute for high-frequency applications because of its high dielectric constant, which improves impedance matching and frequency stability.

7. Conclusion

The study effectively illustrates that $BaTiO_3$-based SMRs are feasible for sophisticated RF filtering and sensing applications. In comparison to conventional piezoelectric materials, $BaTiO_3$ has greater electromechanical capabilities, a high Q-factor, and improved resonance stability, as confirmed by the modeling and simulation results. To achieve effective acoustic wave confinement and improve device performance, the optimized multi-layer Bragg reflector is essential. These results imply that $BaTiO_3$-based SMRs may be a viable option for next-generation RF and MEMS devices, allowing for improved integration in high-frequency electronics, biological sensors, and wireless communication systems.

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