SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V11I10P115

Volume 11 Issue 10, 150-155, October 2024

Original Article

3D Simulation-Based Comparison of Bulk Acoustic Wave FBAR and SMR Technology

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Received: 11 August 2024 Revised: 09 September 2024 Accepted: 11 October 2024 Published: 30 October 2024

Abstract *- Solidly Mounted Resonators (SMRs) and Film Bulk Acoustic Resonators (FBARs) are essential components in RF and microwave applications, each having distinct features that are well-suited to various circumstances. SMRs have a piezoelectric layer sandwiched between two electrodes above a substrate, which ensures a strong construction. In contrast, FBARs use thin piezoelectric sheets on a substrate, resulting in a far thinner design. This thickness difference extends to their operational frequency ranges: SMRs mostly function at lower frequencies, peaking in the gigahertz region. FBARs thrive in higher frequency domains spanning several to tens of gigahertz. This paper compares FBARs with SMRs.The Figure of Merit (FOM) of the BAW resonator is the product of the coupling coefficient and quality factor. The greater kt*Qp product results in better insertion loss across a wider temperature range, allowing longer "hang-time" at the band edges. SMR resonators have a Q value of 970, whereas free-standing membranes have Q values of about 2170. One probable rationale for membrane devices' better Q relative to SMRs is that there are fewer causes of Q loss, resulting in more efficient energy retention within the membrane.*

Keywords *- SMR.FBAR, Quality factor, Losses, RF applications.*

1. Introduction

Beginning in the early 1990s, the mobile communications revolution brought the mobile phone-a portable radio that could be used like a regular phone and virtually anywhere-to the masses in less than ten years. The size and cost of mobile phones decreased at an equally startling rate as their production rose at phenomenal annual rates. The demand for mobile phones led to the need for new types of inexpensive, high-performing, mass-producible, and ultra-miniature components. This need was fulfilled with the development of enabling technologies such as thin Film Bulk Acoustic Resonators (FBAR) and filters. These components function as GHz-range passband filters by excluding undesirable frequencies and selecting the appropriate frequency range for the mobile phone radio to send and receive communication signals.

The type of resonator AWR used is determined by its design, and is differentiated into the said two types: Surface Acoustic Wave (SAW) and Bulk Acoustic Wave (BAW). The resonant frequency and wavelength (λ) are directly related [1]. The physical dimensions of acoustic resonators define their wavelength. In a BAW resonator, the thickness of the piezoelectric layer equals half of the wavelength, while in a SAW resonator, half the wavelength is the width of one piezoelectric material multiplied by the distance to the adjacent piezoelectric material. Lithography capabilities limit SAW resonators for high-frequency applications, whereas BAWs are constrained by deposition processes, which are controlled by the resolution of current production equipment.

2. The Bulk Acoustic Wave concept

Currently, one way for fabrication of bulk acoustic wave devices is FBAR, which Lakin and Wang pioneered in 1981 [2]. The name "BAW" refers to the mechanism in which sound waves pass through the majority of the active layer design (Figure 1(a)). This distinguishes BAW devices from Surface Acoustic Wave (SAW) devices, which travel in a mixed longitudinal-shear Rayleigh mode along the active layer's surface (Figure 1(b)). In both circumstances, the active layer is commonly made of piezoelectric material, which deforms in response to an acoustic wave. BAW and SAW devices rely on piezoelectric and inverse piezoelectric properties to actuate and detect. These phenomena suggest that strain is created in the acoustic layer when voltage is applied to the resonator's electrodes. In contrast, detectable voltage is produced at the electrodes when mechanical strain is created in the acoustic layer. BAW and SAW devices differ fundamentally in their physical configuration. The acoustic layer in BAW devices is part of a stacked construction that limits the acoustic wave. The BAW resonator structure consists of many metal layers that serve as electrodes, with the piezoelectric layer and metal electrodes sitting on the substrate, typically silicon. The two electrodes in SAW devices are interdigitated transducers located on the acoustic layer in the same plane. In some cases, the acoustic layer itself may serve as a substrate. Typically, BAW devices function within the 1 to 10 GHz centre frequencies, while SAW devices are typically found in the 30 MHz to 1 GHz band. On the other hand, depending on the resonant mode and fabrication techniques, both technologies have the ability to increase their core frequency or frequency-band range [3]. The equation can be used to determine the resonance frequency of a BAW resonator based on the thickness t of the piezoelectric material [1]:

$$f_0 = v/2t \tag{1}$$

In this equation, the thickness of the piezoelectric layer is denoted by t, and the sound velocity and frequency of an acoustic wave passing through the bulk of the layer are denoted by v and f, respectively (1).

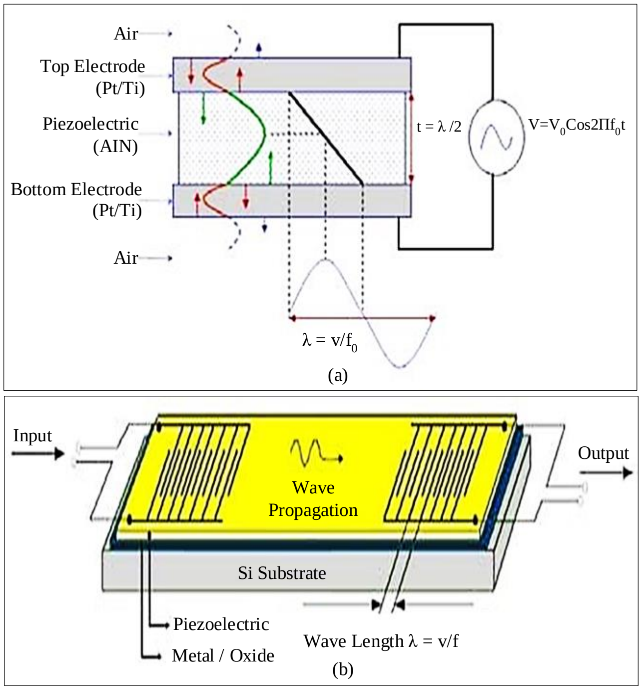

Fig. 1(a) FBAR, and (b) SAW devices.

Figure 1 depicts the acoustic wave transmission in FBAR and SAW devices, respectively. This discovery suggests that the thin film's thickness should be half the acoustic wave's wavelength for the first longitudinal resonance mode. However, we must also account for the electrodes' contribution to the equation since their thickness can reduce the resonance frequency in an electrode-piezoelectric-electrode resonator [4]. As seen in Figure 1, the thickness of the electrodes must be half the wavelength of the acoustic wave to prevent energy from escaping. The device's quality factor, Q amplifies this energy at resonance. More intricate production procedures are needed for the BAW device housing in order to provide acoustic isolation between the resonator and the substrate. Solidly Mounted Resonators (SMRs) are a second-class device in the BAW family [5]. Regarding operating and physical principles, the only difference between SMRs and FBARs is the fabrication method that provides the aforementioned acoustic isolation.

Both forms of BAW comprise a stack of metal, piezoelectric, and metal components. The micro-machined air gap on the FBAR reduces the electromechanical link to the supporting substrate. The SMR device, on the other hand, makes use of a variety of reflective materials called a reflecting mirror or Bragg's reflector [6] (Figure 2). In order to guarantee appropriate impedance mismatching and appropriate isolation between the SMR and the substrate, mirror materials are carefully chosen and engineered [3]. The goal of the acoustic isolation in SMR and FBAR is to create a factor resonator of superior quality. The films are supported by substrates, such as silicon, for mechanical support. Nonetheless, thin film resonator structures must be able to withstand vibration. There are two approaches to providing this:

1) By eliminating the substrate, an air interface is formed at the resonator's lower surface in membrane-type resonators, or FBARs [7, 8].
2) In 1965, Newell proposed Solidly Mounted Resonators (SMR), also referred to as Bragg reflector-based resonators [9].

The reflectors consist of alternating layers of semiconductor material with high and low impedances, each layer measuring λ/4, i.e. a quarter of the wavelength of sound waves and are positioned between the substrate and the resonator. Both types are used in industrial production [10-12].

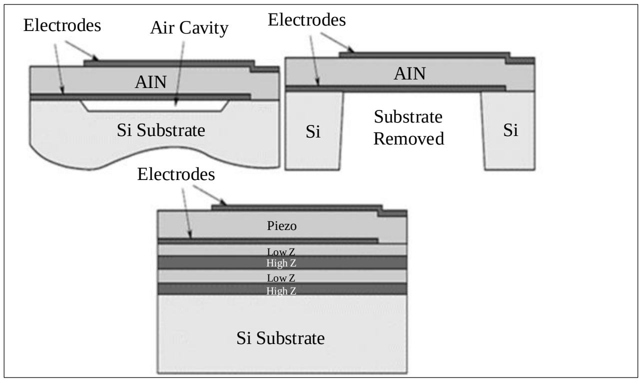

Fig. 2 Fabrication of FBAR resonator using sacrificial layer etching. Self-supported membrane resonators are constructed by through-wafer etching. Resonator structure with Bragg reflector/SMR resonator.

3. Simulation of FBAR and SMR

COMSOL Multiphysics tool is effectively used to simulate Film Bulk Acoustic Resonators (FBARs) and Solidly Mounted Resonators (SMR) to study their performance and optimize the designs. The 3D geometry of the FBAR structure is created by layers such as piezoelectric material, electrodes, and substrate. The piezoelectric material used is zinc oxide (Zno), a biodegradable green material. The different physics used are electrostatic and piezoelectric to analyze mechanical vibrations and to model the electric field and coupling with mechanical deformation. By applying appropriate boundary conditions, the device interacted with its environment. Fixed boundaries for the mechanical components and electrical boundary conditions for the electrodes, such as voltage or charge constraints. By configuring the study to perform a frequency-domain analysis that helped to determine the resonant frequencies and mode shapes of the FBAR and SMR.Both the BAW devices are simulated using COMSOL multi-physics software. The COMSOL 3D structure is depicted in Figures 3, 4 and 5 below.

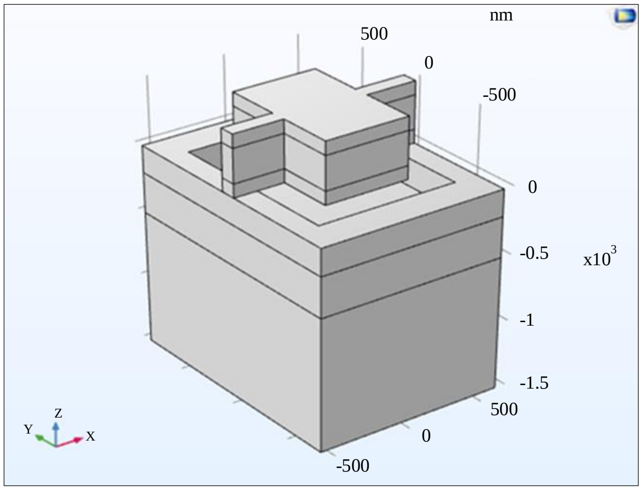

Fig. 3(a) FBAR 3D structure

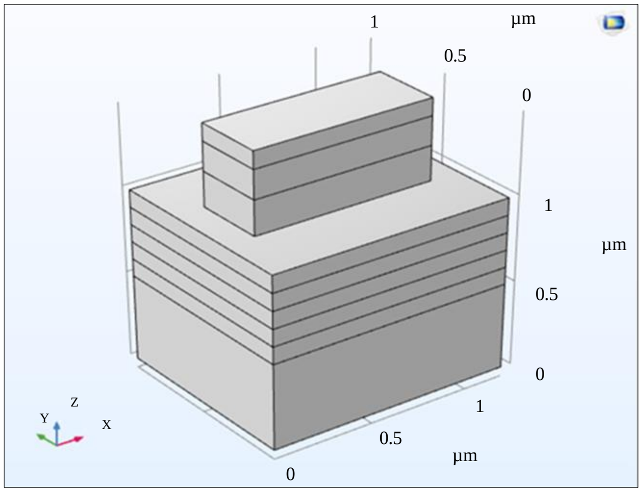

Fig. 3(b) SMR 3D structure

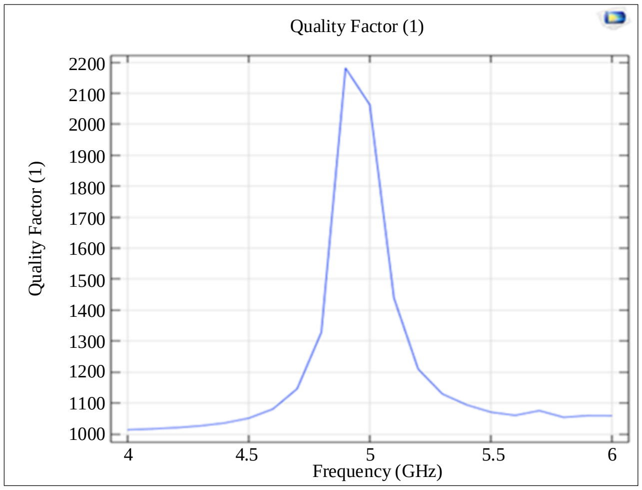

Fig. 4(a) FBAR quality factor Vs frequency

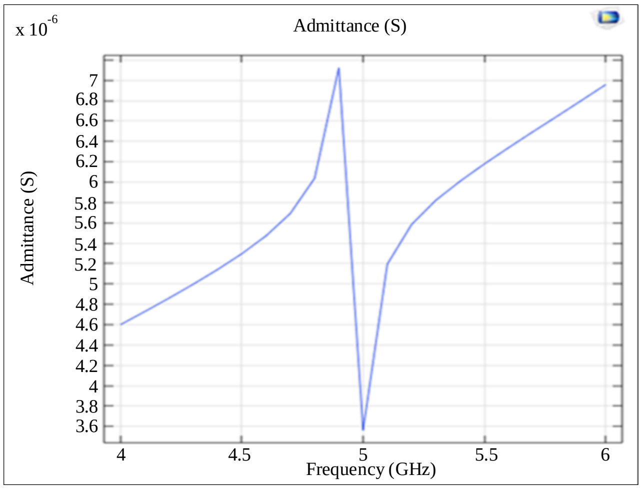

Fig. 4(b) FBAR admittance Vs frequency

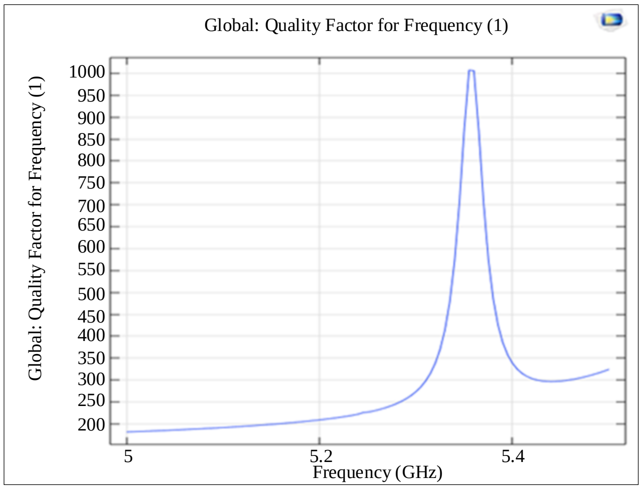

Fig. 5(a) SMR quality factor Vs frequency

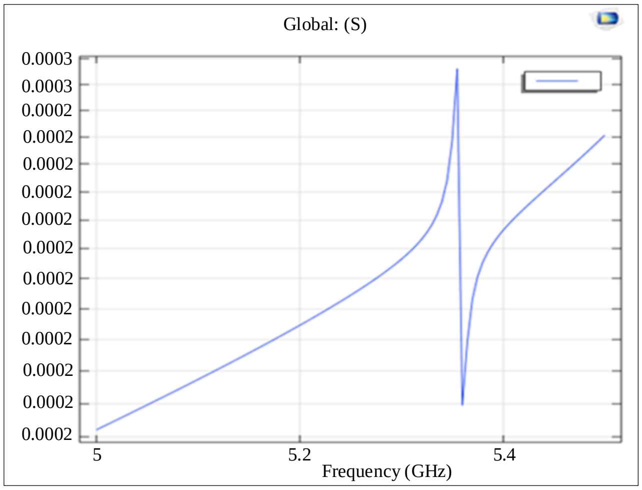

Fig. 5(b) SMR admittance Vs frequency

3.1. Performance Metrics

Performance parameters on which the resonators can be compared are quality factor, coupling coefficient, and figure of merit. Figure 1(a) illustrates how equivalent circuit models of the Butterworth Van-Dyke (BVD) [13, 14] can be used to analyse these parameters.

4. Filter Design

4.1. Electrical Equivalent Circuit Butterworth-Van Dyke (BVD) Model

Both Film Bulk Acoustic Resonators (FBARs) in Figure 6 and Solidly Mounted Resonators (SMRs) in Figure 7 can be accurately represented by the Butterworth-Van Dyke (BVD) equivalent circuit model. This model provides a comprehensive framework for analyzing the behavior and performance of these acoustic wave resonators. The BVD model comprises two main components - a motional arm and a static capacitance. The motional arm consists of Rm (motional resistance), Lm (motional inductance), and Cm (motional capacitance), which together represent the electromechanical response of the piezoelectric material inside the FBAR or SMR structure. The motional resistance (Rm) accounts for the acoustic and dielectric losses in the resonator, while the motional inductance (Lm) models the mechanical inertia of the acoustic wave propagation. The motional capacitance (Cm) reflects the mechanical compliance of the piezoelectric material.

Apart from the motional arm, the BVD model also includes a static capacitance (C0) that represents the electrical capacitance between the two electrodes of the FBAR or SMR. This static capacitance (C0) is a crucial component of the overall equivalent circuit as it captures the electrical characteristics of the resonator structure. By utilizing the BVD model, designers can accurately represent and analyze the performance of FBAR and SMR devices, enabling the optimization of their design and the prediction of their behavior in various applications.

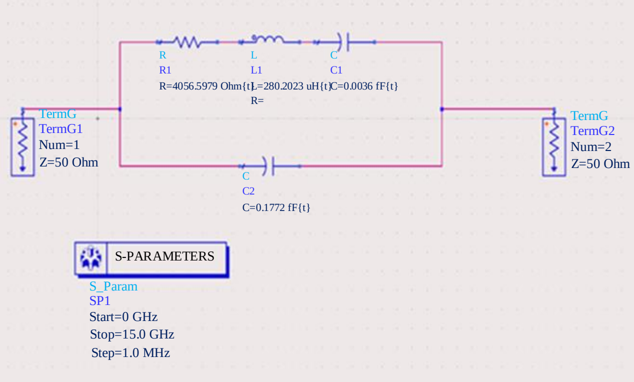

Fig. 6(a) FBAR circuit

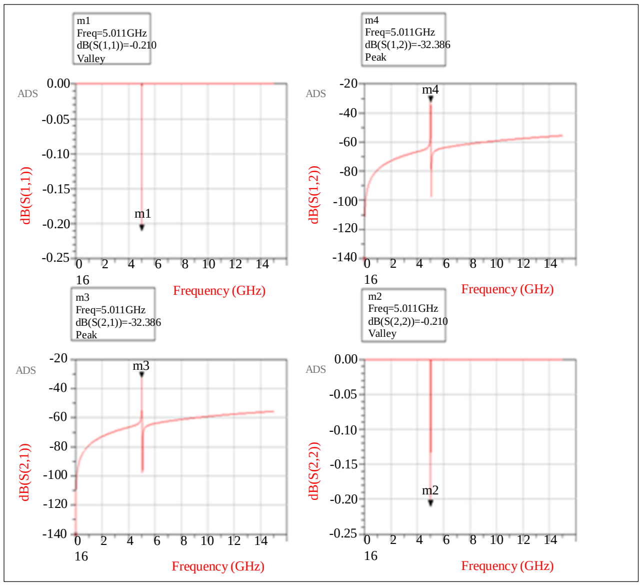

Fig. 6(b) FBAR ADS simulation

5. FBAR Structure and Operation

The Film Bulk Acoustic Resonator (FBAR) is an important component in current wireless communication systems, generating and maintaining sonic waves via piezoelectricity. To build the FBAR, a thin layer of piezoelectric material, most commonly zinc oxide (ZnO), is sandwiched between two metallic electrodes. The piezoelectric material converts it into mechanical energy, causing distortion and producing an audible wave as an electrical signal is delivered across the electrodes. These waves travel through the piezoelectric layer and are reflected via electrode-piezoelectric film connections.

The thickness of the piezoelectric layer is chosen to allow acoustic waves to reverberate, resulting in a standing wave pattern within the FBAR. The FBAR's capacity to generate and maintain acoustic waves is essential to its resonant operation. The piezoelectric layer's thickness gives the FBAR's resonance frequency, with thinner layers allowing for higher frequencies. Designers can meet the specific demands of wireless communication applications by meticulously designing the FBAR structure, including material choices and layer thicknesses.

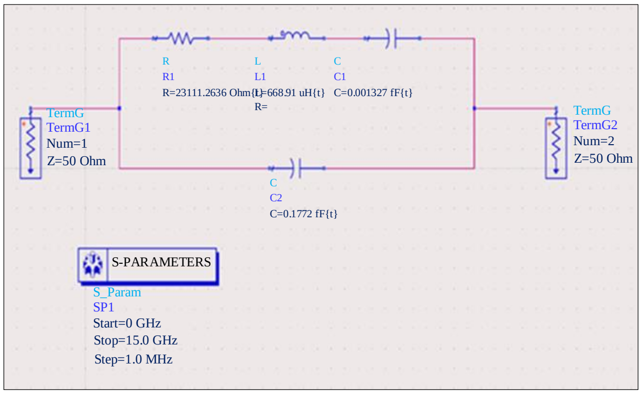

Fig. 7(a) SMR circuit

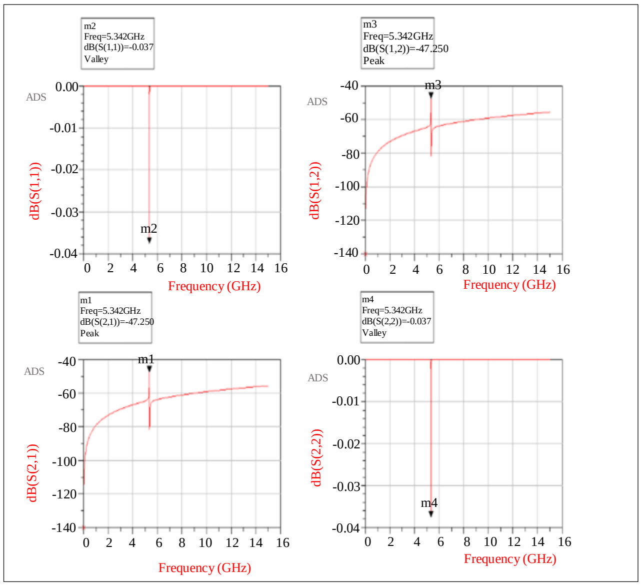

Fig. 7(b) SMR simulation

6. SMR Structure and Acoustic Wave Confinement

Solidly Mounted Resonators (SMRs) share a similar fundamental structure to Film Bulk Acoustic Resonators (FBARs), consisting of a zinc oxide (ZnO) piezoelectric thin film sandwiched between two electrodes. However, the key distinction lies in the way the acoustic waves are restricted within the SMR structure.

Unlike FBARs, which rely on an air cavity underneath the piezoelectric membrane to reflect the acoustic waves, SMRs are "solidly mounted" on a reflective Bragg mirror. A stack of alternating layers with high and low acoustic impedances, usually made of silicon dioxide (SiO_2) and tungsten (W), makes up this Bragg mirror. The specific design of the Bragg mirror, including the number of layers and their thicknesses, is critical in determining its ability to effectively reflect the acoustic waves into the piezoelectric film.

Up until they encounter the Bragg mirror, which is positioned at the bottom electrode contact, sound waves pass through the piezoelectric layer. The acoustic impedance mismatch in the Bragg mirror is caused by layers with alternating high and low impedance. This causes the waves to reflect in the piezoelectric film. This reflection, together with the confinement provided by the Bragg mirror, causes the acoustic waves to resonate within the SMR structure, allowing it to function as a high-performance resonator.

The design of the Bragg mirror is an important component of SMR technology since it directly affects energy dissipation and total resonator performance. By carefully engineering the Bragg mirror, designers can optimize the acoustic wave confinement, minimize energy losses, and achieve high-quality factors (Q) in SMR devices, making them suitable for a wide range of wireless communication applications.

Table 1. Comparison of FBAR with SMR

Parameter	FBAR	SMR
Co (fF)	0.1772	0.1772
Cm (fF)	0.0036	0.001327
Lm (µH)	280.2023	668.91
Rm (Ω)	4056.5979	2311.2636
Q	2170	970
fs (GHz)	5.011	5.342
fp (GHz)	5.062	5.362
k_t^2	0.98	0.9925
FOM	2126.6	962.725

7. Discussion

Surface Micromachined Resonators (SMR) and Film Bulk Acoustic Resonators (FBAR) are both essential components in Radio Frequency (RF) applications due to their high-frequency stability, low power consumption, and compact size. Both SMR and FBAR technologies play critical roles in enhancing the performance and reliability of RF systems. Their unique characteristics make them suitable for various applications, from consumer electronics to advanced communication systems, enabling the development of more efficient and compact devices in today's fast-paced technological landscape.

Bandwidth: SMRs generally offer wider bandwidths, allowing for tuning across various frequencies, while FBARs provide narrower bandwidths with superior selectivity.

Power Consumption: Both SMRs and FBARs are designed for low power consumption, making them suitable for portable and battery-operated devices.

Temperature Stability: FBARs excel in temperature stability, making them preferable for applications where consistent performance across temperature variations is critical, while SMRs may require additional measures to maintain stability.

This comparison highlights the strengths and weaknesses of each technology, enabling informed decisions based on specific application requirements.

8. Conclusion

Solidly Mounted Resonator (SMR) products have just been available in the marketplace. These devices consist of an FBAR directly mounted to a Bragg reflector, made up of alternating layers of semiconductor material with low and high acoustic impedance, each of λ/4 thickness.

Simulation studies show that SMR and FBAR resonators have similar properties in one dimension. However, in SMRs, the kt*Qp product regularly performs worse than free-standing membranes. The preservation of energy inside the underlying Bragg layers has an impact on both kt and Qp in SMRs, which is not observed in FBAR systems.

The larger kt*Qp product in SMRs (Surface Micromachined Resonators) allows for longer "hang-time" at the band boundaries, resulting in lower insertion loss throughout a wide temperature range. SMR resonators have a Q value (Quality Factor) of 970, but free-standing membranes often have Q values of 2170. This differential in Q values could be attributed to membrane devices encountering fewer sources of Q losses, hence improving energy retention.

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