Design and Analysis of Multi-Port SAW MEMS Resonators

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***Abstract*—Surface Acoustic Wave (SAW) resonators are considered very crucial elements in RF technology since they are CMOS compatible. Several designs of multiport SAW resonators are compared regarding their specifications in aim to find a trend between the number of ports and the simulated specifications such as quality factor, insertion loss, phase depth, temperature coefficient of frequency (TCF) and resonant frequency. Analysis is performed to find the lowest TCF value according to the application needed. The operating resonance frequency is obtained from COMSOL Multiphysics frequency domain analysis along with the (TCF). The remaining specifications are calculated from the Butterworth Van-Dyke (BVD) circuit model on Cadence Virtuoso.**

Keywords—acoustic wave; interdigital transducers; temperature coefficient of frequency.

I. Introduction

SAW-based MEMS resonators are a subclass of the acoustic microresonators, which are having an acoustic wave propagation leading to vibration at one of the resonance frequencies. These resonance frequencies are determined by the device dimensions and the material mechanical properties. The resonator structure acts as acoustic cavity that traps the waves propagating in the medium. This trapping is controlled via the design of electrodes and the acoustic layer [1]. The constructive interference between the transmitted and reflected waves concentrates the energy in this cavity. For constructive interference, the waves must be aligned in phase or have $\frac{\lambda}{n}$ phase shift where n is an integer number[1]. Different kinds of surface waves can be utilized for the SAW resonator, namely: Rayleigh, Shear-Horizontal, Love and Sezawa-SAW [2, 3]. In this paper we will use Rayleigh Resonator. In which, the energy confinement occurs very near to the surface.

SAW resonators are based on SAW propagation with an electromechanical transduction mechanism. Accompanied with the appropriate electronic circuit, they can be used as sensors, oscillators or filters. The transduction is done using metallic capacitive electrodes (or piezoelectric electrodes) and a piezoelectric layer for the wave to propagate through, [1]. It has the input transducer electrode which uses the electric signal to generate the mechanical SAW (vibrations) propagating through the piezoelectric layer to the second transducer output electrode which converts this mechanical wave to the electrical domain.

The several multi-port SAW MEMS resonator consists of interdigital transducers (IDTs), a thin or thick piezoelectric layer, and reflectors. The IDT is like a comb-drive and it is used to apply a mechanical stress on the piezoelectric material successively to initiate the surface acoustic waves. The input IDT could be triggered by any form of noise and it starts to oscillate until it reaches the resonance frequency that the resonator is designed to operate at. As the input could be thought of as an AC signal, the polarity of the charges on the IDT fingers starts to alternate from positive to negative and vice versa, creating stress through the piezoelectric material causing deformations to it which in turn create surface acoustic waves and then the waves are transferred to the output IDT.

The waves are then coupled to the output IDT by the same mechanism. The spacing between two successive fingers is equal to $\lambda/2$, where λ is the wavelength of the travelling surface acoustic waves and is given by $\lambda = v/f_r$ where v represents velocity of the surface acoustic waves propagating in the piezoelectric material and f_r represents the resonance frequency. The reflectors are gratings placed on the sides of the device to reflect the wave back to the delay line to minimize substrate losses and obtain a better oscillation condition. In other words, the reflectors make the device act like a resonance cavity.

Acoustic waves propagating through a piezoelectric material are governed by the piezoelectricity equations of state [4]. Following these equations, we can notice that a coupling occurs between the elastic waves and the induced electric field. This coupling results in increase in potential energy in the medium, as a result, the stiffness increases by a factor of $1 + k^2$ where k is the electromechanical coupling coefficient, the effective stiffness is given by:

$$c_{effective} = c_{before}(1 + k^2) \quad (2)$$

$$k^2 = \frac{e^2}{c\varepsilon} \quad (3)$$

Where e, c and ε depend on the direction of propagation. The electromechanical coupling coefficient k is an indication of the electromechanical coupling inside the piezoelectric material and its maximum is unity. To obtain the best results, the electromechanical coupling coefficient k of the piezoelectric material is to be as large as possible, as well as high velocity of waves in the piezoelectric layer, moreover, the piezoelectric material has to eliminate other unwanted bulk waves

Equivalent circuit model:

Here there are two conversions used, firstly, the acoustic forces to the equivalent electrical voltages, and secondly, the surface waves to electrical currents [6]. The Butterworth Van-Dyke model (BVD) is applied in the analysis conducted in this paper. This is a commonly used model for different SAW filters, oscillators and sensors [5, 7]. The model utilizes a circuit with two parallel branches, the R-L-C branch and C-branch as shown in Figure-1.

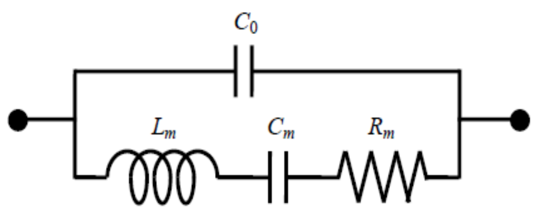

Figure 1- One port IDT equivalent electrical circuit [5].

The first branch maps the series resonance, it occurs when the value of the impedance has a minimum of R, at this value, the inductive part cancels the capacitive part. The latter branch represents the parallel resonance or the so called antiresonance which occurs at higher frequencies where the value of the reactance along the loop becomes zero and the current primarily goes in the loop and does not exceed it. To derive the formulas for those electrical elements, the transfer function is directly expressed using the resonator figure of merit parameters (resonance, anti-resonance and quality factor) and is represented as [5]:

$$Z_{BVD} = \frac{1}{sC_0} \frac{s^2 + s\frac{w_s}{Q} + w_s^2}{s^2 + s\frac{w_s}{Q} + w_p^2} \qquad (4)$$

where the series resonance (resonance) w_s, the parallel resonance (anti-resonance) w_p, and quality factor Q are given by [5]

II. Proposed Designs

There are three main designs investigated in this paper. In each of these designs, the number of IDTs pairs is swept trying to find trends within the resonator parameters. The first design is the basic design with the IDTs being deposited above the piezoelectric material. The second design is the same as the basic design but the only difference is that the IDTs are completely buried in the piezoelectric material and it was done by Silterra Company in Malaysia [8].

The proposed idea in this study is the semi-buried IDTs SAW device, in which half of the electrode is at the surface and the other half is buried in the piezoelectric material. The aim from this design is to investigate if it has better performance than the other two designs. For all the three design families, the number of these pairs ranges from one to 7 IDT pairs. So, the total number of designs simulated are 21 models.

III. Comsol Simulation

The 3D FEA with COMSOL for SAW devices cannot show the admittance graph which has the resonance frequency that are required, to calculate the features of the devices like series resonance frequency, quality factor, insertion Loss, phase depth, TCF, etc. Therefore, the 2D FEA model was used instead. The 2D FEA models in this study was prepared in COMSOL 5.3. The geometry of the design that was simulated is shown in Fig-2.

The resonance frequency of the SAW device depends on the width (λ_0) and the Rayleigh wave velocity of the piezoelectric material which is aluminum nitride in this case. Table 1 shows the wave velocity, width and estimated SAW frequency from COMSOL parameters. The width was calculated by trial and error to get a resonance frequency at exactly 320 MHz which was required.

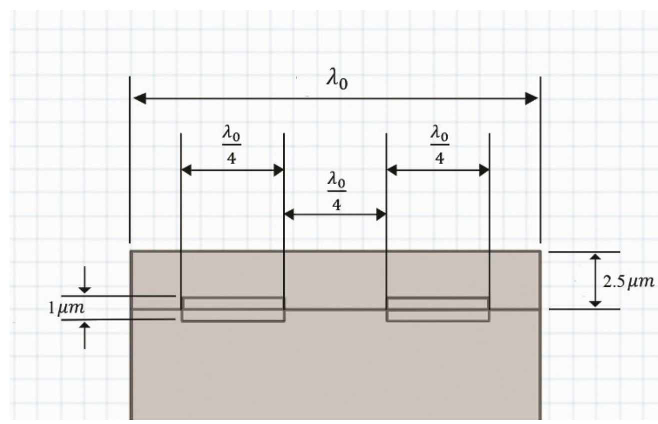

Figure 2- The proposed design of using semi-buried electrodes

TABLE I
THE ESTIMATED RESONANCE FREQUENCY OF THE DEVICE.

V_R	5760 m/s	Rayleight wave velocity
Width	1.763E-5m	Width of unit cell
$f_0 = V_R$ /width	3.2672E8 1/s	Estimated SAW frequency

The voltage is applied on one of the electrodes and the other electrode is connected to ground. The applied voltage is 1 volt. This volt represents a disturbance to the device to. The width of the device must be equal to one wavelength (λ_0), the thickness of the electrodes is 1 μm and the thickness of the surrounding insulator medium (air is this case) is 2.5 µm. These dimensions' constraints are to allow the resonance of the device to take place [9]. The design has boundary conditions as follows. Periodic boundary condition at the two sides of the device. Fixed constraint at the bottom of the piezoelectric material. The thickness of piezoelectric material is $(4\lambda_0)$ or more to avoid the leakage of the waves to the substrate [9].

After extracting the data from COMSOL, other parameters are calculated from cadence simulation below. The reason for these designs is to find the optimum number of ports of each design because the quality factor increases as the number of pairs increases but also the insertion loss increases so it is a case of compromising. Fig-3 shows the simulated 2 pairs of the basic design (which has the electrodes at the surface). The other designs just have different number of pairs of electrodes. And this was done for the Buried and Semi-Buried designs.

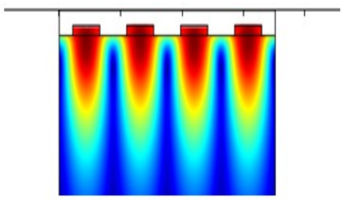

Figure 3- The 2 pairs device of the Basic design and its mode shapes

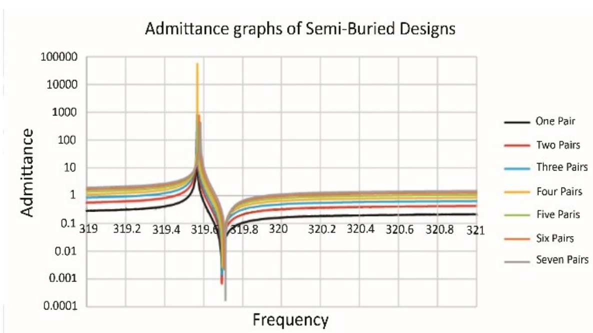

Figure 4- The admittance curves for all number of pairs for the Semi-Buried Design

IV. Cadence Simulation

Cadence virtuoso tool is used to simulate the electrical model of the resonator along with designing a new pierce oscillator circuit to drive the resonator. Pierce oscillator design is first introduced in [3]. The main advantages of Pierce oscillator are that it works on any range of frequencies, and provides a high-quality factor when combined with the resonator due to good stability. It also operates at low power levels which is helpful at high frequency applications. Pierce oscillator can be designed using one transistor, which makes it has no parasitic oscillations [10]. However, the Pierce circuit does have one disadvantage. It needs a relatively high amplifier gain to compensate for relatively high gain losses in the circuitry surrounding the SAW resonator.

Proposed design:

Pierce oscillator circuit consists of four stages of common-source amplifier. The oscillator and the resonator are shown in figure 5. The transistor in the lower level are the main transistor, which provides needed transconductance for the amplifier gain to be high. Each stage has a transistor which provides the bias current and another to perform as the large bias resistor for the gate. The resonator circuit is connected in series with the pierce oscillator as is expected from it to be looking at minimum impedance circuit.

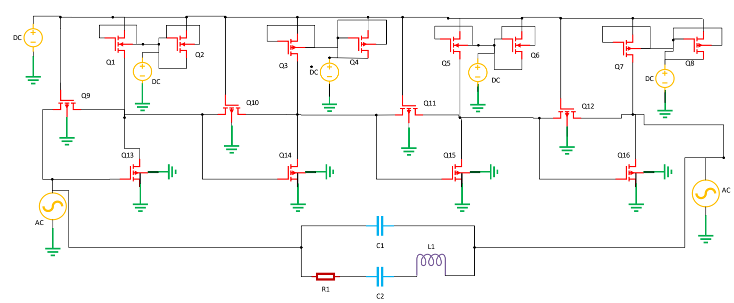

Figure 5- The proposed pierce oscillator

This circuit is biased in weak inversion region. Which results large gate area, weak BW and the resulting gate capacitance is large. This last problem affects the phase shift condition in the operation of the oscillator. On the other hand of these disadvantages, the design has a very large gain which is needed for the operation, low voltage needed to drive the circuit, high transconductance and low power consumption. Gain of the circuit is designed to be high as for the oscillation to start and maintain. The phase is designed to be near 360 degrees to meet the oscillation condition, [10].

Cadence Results:

Transient analysis is performed to see the oscillation output signal. The transient stop time is varied to make sure the oscillation is continuous and maintained. In addition, to get the admittance graph vs frequency, S parameters simulation is required. SP simulations used input and output ports for multi-port SAW devices, to measure Y and S parameters. The Cadence results give the same resonant frequency value as COMSOL results.

V. Temperature Effects On SAW Devices

Temperature variations can cause frequency shifts in SAW devices which is attributed to two main mechanisms; design dimensions change due to thermal expansion and variations of the propagating wave velocity with temperature. From the basic relationship, $f = v/\lambda$, the effect of temperature on frequency is measured by both the delay line shrinkage (λ) and the change of the material properties that changes the wave velocity (v) [11].
The temperature coefficient of frequency (TCF) is defined as the change of frequency with respect to temperature [12].

$\frac{1}{f}\frac{df}{dT} = \frac{1}{l}\frac{dl}{dT} - \frac{1}{v}\frac{dv}{dT}$ where l is the delay line (distance between the input and output IDTs), v is the surface wave velocity, and f is the operating frequency [11]. The first term ($\frac{1}{l}\frac{dl}{dT}$) describes the thermal expansion effect and is calculated according to [13]. The second part, $\frac{1}{v}\frac{dv}{dT}$, is the dominating term. There are different models in the literature describing the dependence between the velocity and temperature. Bleustein-Gulyaev Wave is an accurate model which can be more realistic to describe the surface waves propagation in terms of the material constants [14]. Then, the relation between temperature and these material properties is calculated according to [15]. AlN is used in all the designs to be the surface material as it has the lowest TCF known within the piezoelectric materials and can be compensated.

If the admittance curves are plotted at each temperature for a certain design, a frequency shift is observed. The resonance frequency decreases with increasing the temperature, that is are what the negative The TCF values are calculated for all the proposed designs. For each design family, the values of TCF closer to one another. The difference is higher between the three main design concepts. Results show that buried designs have the lowest TCF values, that is expected because the complete insertion of IDT electrodes inside the piezoelectric material should limit the thermal expansion effect of the electrodes.

VI. Results

The following table compare the performance parameters (the number of IDTs pairs, insertion loss, quality factor, phase depth and TCF) between the designs. The resonance and anti-resonance frequencies for different designs are 319.99 and 320.14 for basic design, 320.48 and 320.58 for buried design and 319.57 and 319.69 for semi-buried design. As expected, the quality factor decreases as the number of pairs increases, except in the semi-buried design. Moreover, the insertion loss in the above surface design decreases as the number of pairs increases. The semi-buried and buried designs did not demonstrate a specific trend.

TABLE II
PERFORMANCE PARAMETERS COMPARISON FOR DIFFERENT DESIGNS

	Basic Design				Buried Design				Semi-Buried Design			
No. of IDT pairs	IL	Q	Phase Depth	TCF	IL	Q	Phase Depth	TCF	IL	Q	Phase Depth	TCF
1	26.3	7799	165	-17.13	31.7	1736	1.1	-15.57	30.4	2693	176	-16.65
2	24.2	7603	155	-17.13	33.8	1668	0.9	-15.58	33.4	1588	177	-16.63
3	20.3	6562	170	-17.14	29	1686	1.5	-15.56	38.2	1510	178	-16.65
4	20.6	5294	173	-17.13	30.6	1612	1.2	-15.56	39.6	2288	179	-16.65
5	19.4	4893	169	-17.19	32.8	1551	1	-15.6	35.4	3355	172	-16.66
6	16	3752	170	-17.19	35	1273	1.1	-15.58	31.7	2887	177	-16.63
7	11.8	1484	49	-17.19	37.8	1241	1.5	-15.57	23.3	3374	172	-16.62

VII. Conclusion

Multiport SAW resonator designs are simulated to compare their performance parameters. The TCF comparison between the three designs shows that inserting the IDTs in the surface is much better for TCF. Picking the number of pairs and the design is dependent on the application needed. TCF variations from the three different designs show that the design can be used as a temperature sensor in case the TCF was high or as a clock generator in case the TCF was low. TCF still can be modified by temperature compensation by adding an oxide layer under the piezoelectric material, which is a recommended approach in the future.

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