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AlN Checker-mode Resonators with Routing Structures

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***Abstract*—The paper presents a two-dimensional piezoelectric aluminum nitride (AlN) Lamb wave resonator (LWR) with a routing structure which can improve the electromechanical coupling coefficient (K_{eff}^2) and reduce spurious modes. In this work, electrodes are arranged on both sides of the piezoelectric layer with routing structure electrical lines which are distributed as a bridge to connect adjacent checkers and this design can successfully enhance acoustic performance. Different shape and thickness design of checker-mode resonators (CMR) are compared in this paper and results show that resonators with circle shaped electrodes have better performance comparable to resonators with hexagon and octagon ones. The simulated resonator with circle shaped electrodes presented in this work resonates at 2.71GHz and achieves high K_{eff}^2 of 5.12% as well as suppressing the spurious modes. Silicon dioxide (SiO_2) between the piezoelectric layer and the routing structure can be used for temperature compensation. This work will play a referential role in the selection of resonator parameters in the future and lay the foundation in the field of high frequency and multi-band RF filters.**

Keywords—piezoelectric resonator, checker pattern electrodes, Lamb wave, routing structure

I. Introduction

With the 5G technology approaching, the demand for multi-band higher-frequency filters has drastically increasing. There are higher requirements for the performance of the acoustic wave piezoelectric resonators. The present work falls under Micro Electro Mechanical Systems (MEMS) technology. As is known to all, the surface acoustic wave (SAW) resonators are widely used in Radio-Frequency(RF) front-end in the early days. However, it can hardly achieve high quality factor (Q) at over 3GHz frequency due to the low phase velocity and lithography limit [1]. In response to the higher frequency market, the bulk acoustic wave (BAW) filters are provided due to lower insertion loss, better selectivity, higher power handling, etc [2]. Q and K_{eff}^2 are vital parameters for a filter in multi-band radio-frequency system. The film bulk acoustic resonators (FBAR) are widely used in RF front-end components for its high Q and large K_{eff}^2. However, FBAR can hardly achieve multi-frequency on single-chip because its resonance frequency is defined by physical stack film thickness [3].

The research of Lamb wave piezoelectric devices, which are of interest for applications in both frequency control and sensing, can be traced back to the early 1990s. Professor Richard M. White of the University of California at Berkeley introduced interdigitated (IDT) electrodes to excite body waves in piezoelectric films [4]. High Q LWRs are demonstrated low noise, low loss and thermally stable performance. LWR can solve the problems faced by SAW for the high frequency limit and faced by FBAR for the multiple frequency capability [5]. The resonance frequency of the LWR can be tuned by lithography technology which features robust designs and integrated circuit (IC) compatible for future needs [6]-[8].

The checker-mode resonator (CMR) is a kind of two-dimensional LWR which has rapidly developed in recent years [9]-[13]. Different from FBAR, LWR couple both lateral excitation and thickness excitation while the FBAR generally utilize thickness excitation [14]. The motivation of CMR is even more complicated. CMRs with checker-patterned electrode pads which are divided into two groups of electrodes can realize balanced differential design, meanwhile, it has a FBAR comparable high K_{eff}^2 and Q for a filter design which make it possible as a candidate for traditional SAW and FBARs. The resonant frequency of the CMR depends on the size of the checker-patterned electrodes and the distance between them. However, the checker-patterned electrode pads would easily cause spurious modes which may greatly reduce the performance of the resonator. As a contrast, The CMR with an ideal routing structure can reduce spurious modes as well as improving the K_{eff}^2 of the resonator. The width of the electrical lines should be made as narrow as possible. On the one hand, the narrow electrical lines would increase the impedance which decreasing the power handling of the device. On the other hand, the cross areas between the top electrical lines and the bottom electrical lines would also generate a thickness mode acoustic wave. Therefore, to avoid the effect of the lateral spurious excitation due to the electrical lines and improve the power handling, the design of routing structure need to optimize and enhance the acoustic performance of the CMR.

Series of CMRs with different shapes of electrical pads were simulated in the work. The checker-patterned electrode pads with a routing structure are distributed along both sides of the piezoelectric layer. The routing structures are distributed as a bridge to connect adjacent checkers which can successfully enhance acoustic performance. The checker-patterned electrode pads are directly coupled with the piezoelectric thin film while the electrical connection lines are routed on a thin layer of SiO_2 which prevent the electrical field formed between the electrical lines both in thickness and lateral directions. Meanwhile, SiO_2 between the piezoelectric layer and the routing structure can be used for temperature compensation to improve the temperature coefficient of frequency (TCF) [15]. With such structure, the checker-mode three-dimensional acoustic wave could be formed in the resonator. Through adjusting the shape of the electrode pads could increase the K_{eff}^2 of the resonator and suppress spurious modes. Furthermore, different size (R) and thickness (H) of electrode pads are compared in this work. This work will play a referential role in the selection of resonator parameters in the future.

II. Sructure Design

The embodiments of the present paper fall under the piezoelectric micromechanical resonators for applications such as sensors, RF-MEMS oscillators and filters. This work aims to enhance the performance of the CMR by applying appropriate patterned electrode pads to excite a three-dimensional electrical field.

Fig. 1 shows the configuration of the CMR. There are three different shapes of electrode pads with a routing structure symmetrically checker patterned on both surfaces of a piezoelectric plate. The process begins with a layer of Al electrical connection lines deposited and patterned. A layer of SiO_2 was deposited on the surface of the substrate. Chemical Mechanical Polishing (CMP) process will be used to expose routing structures for the next connection with the bottom electrodes. Next, deposit a layer of AlN as piezoelectric thin film. Then, the top electrodes fabrication follows. The first step for the top electrodes is symmetrically checker patterning the electrode pads on the AlN plate, after that, a layer of SiO_2 would be deposited to cover these electrode pads, followed by electrical metal deposition and electrical lines patterning. By now, the top routing structure electrodes formed. The CMR is released by using vapour hydrofluotic (VHF) acid. The cross section of the CMR with a routing structure can be seen in Fig 1(d). The checker-patterned electrode pads are directly cover the AlN plate while the electrical connection lines are routed on a layer

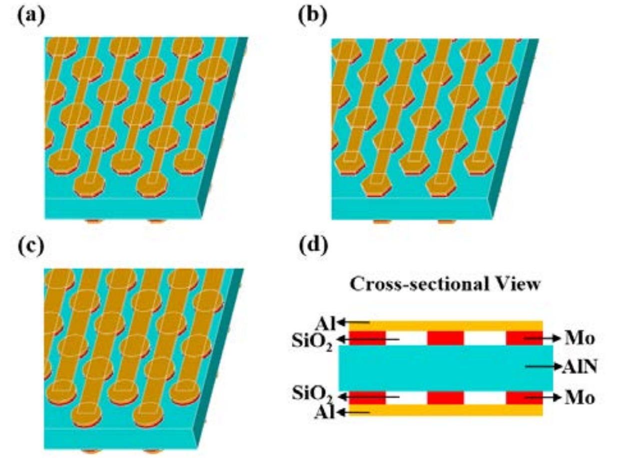

Fig. 1. An illustration of configuration for the CMR with routing structure electrodes: (a) CMR with hexagon shaped electrodes. (b) CMR with octagon shaped electrodes. (c) CMR with circle shaped electrodes. (d) cross section view of the resonator.

of SiO_2. When an alternative AC signal is applied on the two groups of routing structure electrical lines, the electrical field will be concentrated on those checker-patterned electrode pads. Specifically, adjacent electrodes on the same side of the AlN piezoelectric layer are applied the signals of opposite potential while the symmetric electrodes on the different sides of the AlN piezoelectric layer are also applied opposite potential signal. In general, a three-dimensional (3D) electric field would be generated in the resonator. Due to the arrangement of the checker-patterned electric pads, the generated electric filed is excited by cooperative coupling the two intersecting laterally electric field and a thickness electric field. The 3D electric field will generate two intersection transverse acoustic waves within the piezoelectric material that are simultaneously excited on both sides of piezoelectric layer by the lateral excitation field between the adjacent electrode pads, meanwhile, the thickness electric field formed between each couple of top and bottom electrode pads can excite longitudinal acoustic waves. Unlike the SAWs and FBARs, Lamb waves in CMRs have a 3D acoustic waves which can enhance the performance of the resonator.

III. Simulation Results And Discussion

Simulation results of different configuration of the CMR with a routing structure are shown in this section. All results are simulated in the finite element analysis software ANSYS. In this simulation, the thickness of the AlN piezoelectric layer is defined 1.1μm while the thickness of the Mo electrode (H) is 0.14μm. Meanwhile the thickness of the routing structure is 1.0μm. By changing the shape of the checker patterned electrode pad, impedance curves of CMRs with three kinds of electrode shapes are illustrated in fig.2. Comparing the three impedance curves, it can be seen that the ripples of impedance curve of the resonator with circular patterned electrode is obviously reduced. Resonators with circle shaped electrodes have better performance comparable to resonators with hexagon shaped electrodes and octagon shaped electrodes. According to the (1), the simulated resonator with circle shaped electrodes presented in this work resonates at 2.71GHz and achieves high K_{eff}^2 of

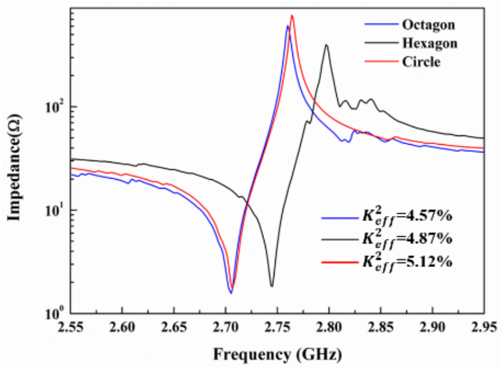

Fig. 2. Impedance curve of three electrode designs.

5.12% which the simulated series resonant frequency (f_s) is 2.707 GHz, and the parallel resonant frequency (f_p) is 2.764 GHz. It also can be observed that the spurious modes are successfully suppressed in this design.

$$K_{eff}^2 = \frac{\pi^2}{4}\frac{f_p - f_s}{f_p} \tag{1}$$

In this design, total displacement at resonance frequency using 3D modeling are demonstrated in fig.3(a). The mode shape shows that the big displacements happen at checker-patterned electrodes. The electrode with a positive voltage expands and the negatively charged electrode compresses, which is consistent with the piezoelectric properties of the piezoelectric material. Fig. 3(b) illustrates the electrical potential of the CMR with circle shape electrodes in this configuration. Positive and negative voltages are alternately applied to the circle shaped electrode, thus exciting a 3D electric field. The coupling of the transverse electric field and the longitudinal electric field can be clearly seen from the fig.3(b) which is consistent with the theory. The maximum displacement also corresponds to the maximum potential.

In order to further analysis the influence of the size of circular electrodes on the performance of resonators, adjusting the radius of the circular electrode pads (R) while the other design parameters remain the same. Fig. 4(a) is a schematic view of the structure. As illustrated in Fig. 4(b), it can be found that the resonance frequency tunable range is 1.71 GHz when the radius of the electrode is changed by 1 μm. When the radius is reduced to a certain extent, the parasitic mode is generated near

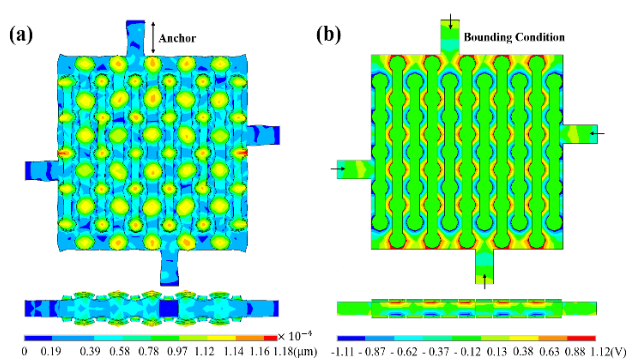

Fig. 3. (a) Simulated total displacement at resonance frequency using 3D FEM modeling. (b) Electrical potential of the CMR with circle shape electrodes in this design.

the resonance point. Therefore, in practical applications, the size of the electrode should be reasonably planned. If the electrode size is too small, the processing process will be difficult. More importantly, as the electrode size is reduced, it is not conducive to suppressing the spurious mode, the Q value is declining, and the performance of the resonant device is somewhat impaired.

Furthermore, through changing the thickness of the electrode pad (H) to explore the effect on the performance of resonator while radius of the electrode (R) is defined 0.58um. Fig. 5(a) is a schematic structural view corresponding to the impedance curve, and Fig. 5(b) is a sectional view thereof. It can be concluded by the fig. 5(c) that as the thickness of the electrode increases, the resonant frequency of the CMR gradually decreases. The thickness of the electrode is equivalent to the introduction of the equivalent sound path, and the longer the sound path is introduced, the lower the resonance frequency will be. It is obvious that, with the thickness of the electrode increases or decreases, spurious modes will be introduced. Particular frequency bands are needed when designing filters, especially higher frequency RF devices oriented to 5G. In this case, the electrode thickness should be minimized, but if the electrode is too thin, it will affect the mechanical fastness. Therefore, it is necessary to choose a suitable electrode thickness. The robust design makes the K^2_{eff} slightly float as the thickness increases.

IV. Conclusion

Series of resonators with different shapes and thickness of electrical pads were simulated in this work. Results showed that resonators with circle shaped electrodes have better performance comparable to resonators with hexagon shaped electrodes and octagon shaped electrodes. The simulated resonator with circle shaped electrodes presented in this work resonates at 2.71GHz

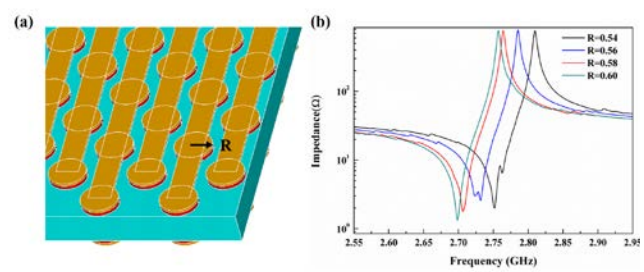

Fig. 4. (a) An illustration of the configuration. (b) Impedance curve of different size electrode.

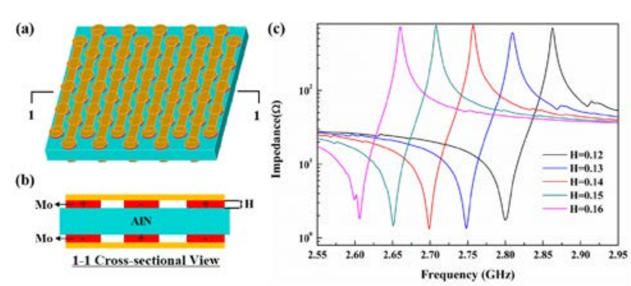

Fig. 5. (a) An illustration of the structure. (b) Cross-section view of the design (c) Impedance curve of different electrode thickness.

and achieves high K_{eff}^2 of 5.12%. It also can be observed that the spurious modes are successfully suppressed in this design. This work lay the foundation in the field of high frequency and multi-band RF filters.

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