Investigation of the BAW-like Coupled Bulk Acoustic Resonators (CBAR) and Method to Further Improve the Coupling Coefficient

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***Abstract*—A thickness and lateral mode coupled film acoustic resonator (CBAR) with k^2_{eff} comparable to the FBAR has been proposed and demonstrated previously. This paper further systematically investigate the impact of the design parameters on the resonant frequency and k^2_{eff} of this CBAR structure. A method to further improve the k^2_{eff} by filling the finger gaps with dielectric material is also proposed.**

***Keywords*—Acoustic resonator, coupling coefficient, high frequency**

I. Introduction

Currently, the bulk acoustic wave (BAW) technology is dominating the filtering market for 5G communication, due to its high frequency capability with low film thickness [1]. The main drawback of the BAW resonators is the resonant frequency restriction by the film stack, thus BAW filters for different frequency bands can only be achieved by tuning the thickness of the whole stack, which makes it challenging to fabricate filters for various frequency bands on the same wafer.

To address this problem while still remaining the high frequency capability of BAW resonators, various resonator designs have been proposed to enable the BAW technology with lithographic frequency tenability. A common approach is to replace the plate electrode by interdigitated electrode fingers (IDE) in surface acoustic wave (SAW) technology to enable the lateral modes besides the thickness modes. Typical lithographically tunable resonator structures include the two-dimensional-mode resonator (2DMR) [2], Lamb wave mode resonators [3], two-dimensional-resonant rods (2DRRs) [4], laterally coupled alternating thickness (LCAT) mode resonators [5], and cross-sectional-Lame-mode resonators (CLMR) [6].

However, the aforementioned resonator designs with lithographical frequency tunability usually suffer from the poor effective coupling coefficient (k^2_{eff}), which is normally less than half of the traditional BAW resonators with the same materials and stack. This low k^2_{eff} can hardly meet the high requirement of the filters for 5G technology in terms of the bandwidth. Y. Zhu et al. has proposed and demonstrated a new resonator structure, named BAW-like coupled bulk acoustic resonator (CBAR), in IUS 2019 [7]. This type of structure enables the design freedom of frequency tuning by electrode patterning while achieving a high k^2_{eff} comparable to the BAW resonators.

In this work, the impact of the design parameters, including the electrode finger pitch, electrode finger width and space, on the frequency and k^2_{eff} of this CBAR structure are systematically investigated. A method to further improve the k^2_{eff} by filling the finger gaps with dielectric material is proposed and investigated. The resonators with different filling thickness and pitch have been simulated and compared. Also the filling material deposited by ALD technology has been simulated and the impact has been investigated.

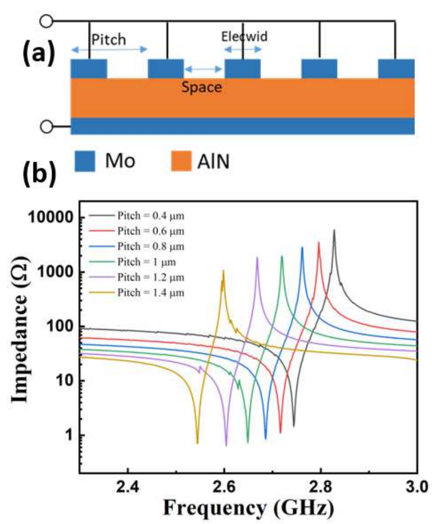

Figure. 1 (a) The schematic cross-section of the CBAR. (b) The impedance response of the CBAR with different pitches.

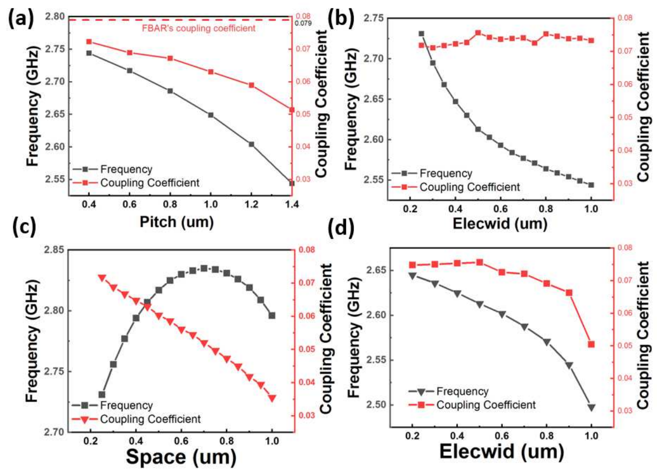

Figure. 2 Summarized relationship of resonant frequency and k^2_{eff} vs: (a) top electrode pitch; (b) width of the electrode finger; (c) space between two adjacent electrode fingers; (d) width of electrode finger with constant duty ratio (width/space = 2).

II. Coupled Bulk Acoustic Resonator

The cross-sectional schematic of the CBAR structure is shown in Figure 1(a). The piezoelectric layer is sandwiched between the top comb-shape electrode and bottom electrode plate. All the top electrode fingers are electrically shorted by a bus. AC signal with opposite polarity is applied on the top comb electrode and bottom plate electrode. The definition of the electrode pitch, electrode width (shorted as elecwid) and the space between adjacent fingers are also illustrated in Figure 1(a). The top and bottom electrode is molybdenum and the AlN is used as the piezoelectric layer. The thickness of the stack is 0.26 μm/1 μm/0.2 μm.

To evaluate the impact of the design parameters, the frequency response of the resonators is quantified by 2-dimentional finite element modeling (FEM) in the COMSOL software. In this work, the resonant frequency (f_s) and effective coupling coefficient (k^2_{eff}) are investigated with varying the different design parameters. The k^2_{eff} is calculated by the following equation:

$$k_{eff}^2 = \frac{\pi}{2}\frac{f_s}{f_p}\frac{1}{\tan(\frac{\pi}{2}\frac{f_s}{f_p})}$$

Where f_p refers to the anti-resonant frequency of the resonator.

The simulated impedance of the resonators with sweeping electrode pitch, in which the electrode finger width is identical to the space, are plotted in Figure 1(b). The spurious modes, which are common in other resonator designs with interdigital electrode fingers, cannot be found in this CBAR devices within the pitch range above. The impact of electrode pitch, width, space on the f_s and k^2_{eff} of the CBAR have been summarized in Figure 2 (a) to (c), respectively. With the pitch increasing from 0.4 μm to 1.4 μm, the f_s decreases from 2.75 GHz to 2.55 GHz while the k^2_{eff} decreases from over 7% to around 5%. As a reference, the k^2_{eff} of the film bulk acoustic resonator (FBAR) with the same stack and thickness is simulated as 7.9%. With the electrode fixed at 0.3 μm, the impact of sweeping electrode width is illustrated in Figure 2 (b). The results show that with fixed electrode space, the sweeping electrode width will enable similar frequency tunable range while maintaining the k^2_{eff} at over 7%, which means a high k^2_{eff} comparable to the FBAR can be achieved in a wide frequency range with the CBAR devices. The impact of electrode space with width fixed at 0.3 μm is summarized in Figure 2 (c). Unlike the electrode width, the increasing space will dramatically reduce the k^2_{eff} from 7% to around 3.5%, and the f_s will increase then decrease with the increasing space. The electrode width sweeping with a constant duty ratio (width/space=2) is also investigated and the results are shown in Figure 2 (d). With a larger duty ratio, the resonators perform better than the width equaling to space cases with similar pitch value, in terms of the k^2_{eff}. The simulation results show that to achieve a high k^2_{eff}, it's better to have a small space while sweeping the electrode width for tuning the resonant frequency.

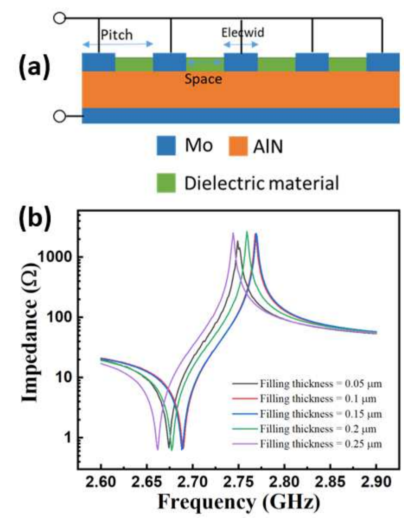

Figure. 3 (a) The schematic cross-section of the CBAR with dielectric filling the electrode intervals. (b) The impedance response of the CBAR with different thickness of the dielectric filling.

III. Method to Improve the K^2_{EFF}

An approach to further improve the k^2_{eff} of the CBAR is proposed by filling the electrode intervals with the dielectric material, illustrated in the Figure 3 (a). This filling aims to match the acoustic dispersion between the active area with top electrode and the in-active area without top electrode covering. The simulated frequency responses of the CBAR devices with different thickness of the dielectric filling are plotted in Figure 3 (b). Introducing of the dielectric filling doesn't introduce any spurious modes around the main resonance of the CBAR devices. The f_s and k^2_{eff} of the CBAR devices with various pitches and filling thickness have been summarized in the Figure 4 (a) and (b), respectively. The f_s and k^2_{eff} of CBAR devices with sweeping pitch and without dielectric filling are also plotted into the figures as reference. Results show that the dielectric filling will degrade the frequency tunable range, and with the same pitch sweeping range, thicker filling will have smaller frequency range. As for the k^2_{eff}, for all the electrode pitch ranging from 0.4 μm to 1.4 μm, the dielectric filling will improve the k^2_{eff}, compared to the without filling case. And the k^2_{eff} gradually rises with the dielectric filling approaching the top electrode thickness. For the pitch = 1.4 μm case, the improvement of k^2_{eff} can be as high as 1.5%. These simulation results show that for this dielectric filling method, the k^2_{eff} is improved with sacrificing the lithographic frequency tunable range. This trade-off between the f_s tunable range and the k^2_{eff} will be the key consideration in the design of this type resonators.

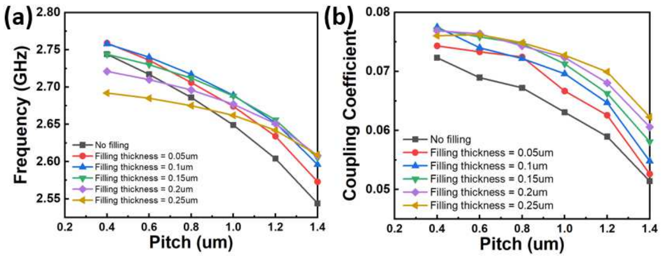

Figure. 4 Summarized performance of the CBAR devices with sweeping electrode pitch and various thickness of the delectric filling. (a) Resonant frequency vs pitch & fillilng thickness; (b) k^2_{eff} vs pitch & filling thickness.

The atomic layer deposition (ALD) is a common technology for dielectric material deposition. The features of the ALD technology is that the sidewall will also be covered during the deposition. To validate the feasibility of the proposed k^2_{eff} improvement method, the dielectric material deposited by ALD without additional etching, illustrated in Figure 5 (a), has been investigated via FEM simulations. The summarized f_s and k^2_{eff} of the CBAR with pitch = 1μm and sweeping ALD filling thickness has been illustrated in the Figure 5 (b). This ALD filling usually acts as a loading layer to tune the resonant frequency, and compared to no filling case, this ALD filling can also improve the k^2_{eff}, and the improvement is around 1%.

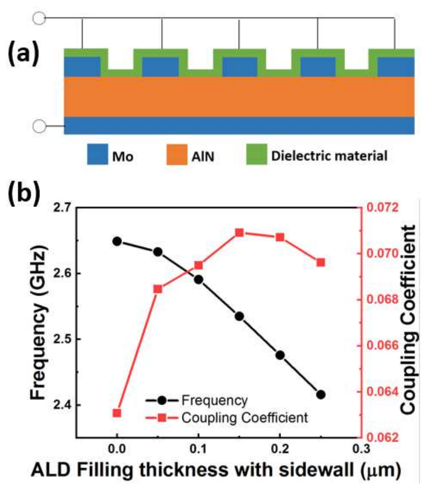

Figure. 5 (a) The schematic cross-section of the CBAR with dielectric filling deposited by ALD technology. (b) Summarized f_s and k^2_{eff} of the CBAR with pitch = 1μm and sweeping filling thickness.

IV. Conclusion

In this work, the impact of the geometry parameters on the thickness and lateral mode coupled film acoustic resonator are systematically investigated to provide the guideline for the device design. Simulation results show that a fixed small electrode space with various electrode width for lithographic frequency tunability is an appropriate strategy in terms of maintaining a high k^2_{eff}. Further a method to improve the k^2_{eff} of the CBAR by filling the intervals with dielectric material is proposed and verified via simulation. This dielectric filling is efficient for all pitch cases regarding the k^2_{eff} improvement but will hinder the lithographic frequency tuning capability. ALD technology for the dielectric filling has also been proved to be efficient in terms of the k^2_{eff} improvement.

Acknowledgment

This work was supported by the Science and Engineering Research Council of A*STAR (Agency for Science, Technology and Research), Singapore, under Grant no (A20G9b0135).

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