Electrode Design of AlN Lamb Wave Resonators

Jie Zou and C.S. Lam
Skyworks Solutions, Inc.
Irvine, CA, USA
jie.zou@skyworksinc.com, C.S.Lam@skyworksinc.com

Abstract—The impact of electrode configurations, materials, thicknesses and interdigital transducer (IDT) duty factor (DF) on performance of aluminum nitride (AlN) Lamb wave resonators is analyzed and summarized for the first time in this study. By careful design and selection of the transducer and bottom electrodes, the effective electromechanical coupling coefficient ($k^2_{\text{eff}}$) of the AlN Lamb wave resonator can be boosted from ~2% to values close to 7%. The results reported in this paper lay the foundation for transducer designs of AlN Lamb wave resonators.

Keywords—Lamb wave resonator, aluminum nitride, effective coupling coefficient, electromechanical coupling coefficient, filter bandwidth.

I. INTRODUCTION

In response to the drastically increasing demand for more and faster data delivery in wireless mobiles, new and tougher specifications for filters and multiplexers come along for supporting the crowded spectrum and in seek of future opportunities [1], [2]. It is well-known that electroacoustic devices, such as surface acoustic wave (SAW) resonators and film bulk acoustic resonators (FBARs) offer attractive features in low-loss radio frequency (RF) bandpass filtering. However, the high frequency ($f_s$) limitation in SAW resonators and multi-frequency difficulty in bulk acoustic wave (BAW) resonators poses obstacles for them to further enable highly integrated front-end architecture, featuring high performance and small size for the future needs.

A new class of piezoelectric AlN Lamb wave resonator (LWR) utilizing the lowest-order symmetric (S₀) mode attracts wide attention recently since it solves the high frequency limitation faced by the SAW resonator and the multiple frequency capability problem faced by the FBAR: its high phase velocity ($v_p$) up to 10,000 m/s easily enables $f_s$ up to 4 GHz, and the interdigital transducers (IDTs) lithographically defines the resonance frequency $f_c$. In addition, the AlN LWR exhibits weak phase velocity dispersion characteristics which allows for fabrication tolerance, a small temperature coefficient of frequency (TCF) of around –26 ppm/°C, high quality factor (Q) of ~2,500–4,000 because of the suspended plate feature, and the CMOS-compatible ability by using the sputtered c-axis oriented AlN [3]–[15].

 Nonetheless, the current reported AlN LWRs usually show a moderate effective coupling coefficient ($k^2_{\text{eff}}$) of around 2%, posing a limit to the supporting filtering bandwidth (BW). Despite all the $k^2_{\text{eff}}$ enhancement tricks reported previously [16]–[19], by simply designing electrodes and optimizing for electro-mechanical transferring condition in the $S_0$ Lamb wave resonance, the $k^2_{\text{eff}}$ can be boosted to a large extent [20]–[27].

II. ELECTRODE CONFIGURATIONS

Although the Alder’s approach has been widely adopted in

![Fig. 1. Simulated effective coupling coefficient $k^2_{\text{eff}}$ using FEA for four electrode configurations. The electrodes are assumed to be infinitely thin.](image1)

![Fig. 2. FEA simulations of $v_p$ of the AlN Lamb wave resonators with different IDT electrodes when the electrode thickness is equal to 0.02λ.](image2)
evaluating the electromechanical coupling coefficient \( k^2 \) for piezoelectric LWRs [11], [28], it simplifies the model by only considering the piezoelectric material properties and electrical excitation boundary conditions without distinguishing the difference in actual potential fields, the IDT reflection levels, and the mechanical loading effect. In order to count in all the important effect as involved in a real resonator, the two-dimensional (2D) finite element analysis (FEA) method is adopted herein and the effective coupling coefficient \( k^2_{\text{eff}} \) is calculated from the resonance frequency \( f_s \) and anti-resonance frequency \( f_p \) distance in the frequency domain analysis. The periodic boundary condition is considered and applied to the left and right boundaries of the AlN plate in the simulation so the reflection affect caused by the free edges can be ignored in \( k^2_{\text{eff}} \) calculation.

Fig. 1 shows the FEA-simulated \( k^2_{\text{eff}} \) of the AlN LWRs with four transducer configurations: (a) the single-IDT electrode configuration, (b) the single-IDT/grounded-bottom electrode (BE) configuration, (c) the single-IDT/ floating-BE configuration, and (d) the double-IDT electrode configuration. The IDT and bottom electrodes are assumed to be infinitely thin herein to only compare the effective coupling coefficient of the four electrode configurations.

As illustrated in Fig. 1, the double-IDT configuration enables a larger \( k^2_{\text{eff}} \) in comparison to the other configurations and the single-IDT configuration shows the smallest among the four configurations. The \( k^2_{\text{eff}} \) for the single-IDT and double-IDT configurations peaks when the AlN thickness \( (h_{\text{AlN}}) \) equals \( 0.5\lambda \), while the \( k^2_{\text{eff}} \) of the IDT/grounded-BE and IDT/floating-BE configurations reaches maximum when the AlN plate is thin \( (h_{\text{AlN}}/\lambda < 0.2) \). The single-IDT/floating-
BE configuration shows a larger $k^{2}_{\text{eff}}$ than IDT/grounded-BE configuration because of the smaller static capacitance ($C_0$) [4], [5].

III. ELECTRODE MATERIALS

A. Phase velocities

The impact of different electrode materials on the phase velocity when $h_{\text{metal}/\lambda} = 0.02$ is shown in Fig. 2, and the material constants of different metals used for calculation are from [28]. When the AlN thickness is thicker than 0.1$\lambda$ ($h_{\text{AlN}/\lambda} > 0.1$), the loading effect of different metal materials is fully proportional to the densities of metals. When the AlN is very thin, the stiffness of the metal also impacts the loading effect, and the phase velocity of the S0 Lamb wave mode in the bilayer is fully proportional to the equivalent phase velocity in the metal. Therefore, generally the heavier metal has a stronger loading effect on the phase velocity. However, soft metals also decrease the phase velocity of the S0 mode if the AlN thickness is thinner than 0.1$\lambda$ ($h_{\text{AlN}/\lambda} < 0.1$).

B. Electromechanical coupling coefficients

Fig. 3(a)–(d) show the effect of seven different metal electrode materials on the $k^{2}_{\text{eff}}$ of the S0 mode AlN LWRs under different electrode configurations. The electrode layers decrease the $k^{2}_{\text{eff}}$ when AlN is very thin and enhance the $k^{2}_{\text{eff}}$ when the AlN plate becomes thick. When the AlN is thin, the piezoelectric-dead metal deviates the acoustic wave field away from the piezoelectric AlN layer and thus reduces the $k^{2}_{\text{eff}}$. It is clear that the heavier metal has a stronger loading effect on $k^{2}_{\text{eff}}$. When the AlN plate becomes thick, the existence of the metal layer can boost the $k^{2}_{\text{eff}}$ due to the large acoustic impedance ($Z = \sqrt{E \times \rho}$) and increased reflectivity, and the strength of $k^{2}_{\text{eff}}$ is proportional to the acoustic impedance of the metal. The double-IDT configuration gives $k^{2}_{\text{eff}}$ to above 6% when the metals with a large acoustic impedance (W, Pt, Au, and Mo) are employed as the electrodes.

C. Different materials combinations

Although a floating bottom electrode layer increases the $k^{2}_{\text{eff}}$, compared to the single-IDT configuration as shown in Fig. 1, the additional heavy metal layer can draw the $k^{2}_{\text{eff}}$ back intensively as depicted in Fig. 2(c). Therefore, a light (i.e., small density) metal can be used for the material of the bottom electrode while the metal with a large acoustic impedance is employed in the IDT to maximize $k^{2}_{\text{eff}}$.

To validate the novel approach, the $k^{2}_{\text{eff}}$ is calculated and compared for different combinations of W and Al as the IDT or bottom electrode materials, since Al has small density and low acoustic impedance whereas W has large density and high acoustic impedance. Fig. 4 presents the comparison of the different combinations of metal material for the single-IDT/floating-BE configuration. When the AlN layer is very thin, the $k^{2}_{\text{eff}}$ simply depends on the density of the metal material. As the AlN plate becomes thick, the combination of large acoustic impedance material (W) as the IDT and light metal (Al) as the bottom electrode gives the largest $k^{2}_{\text{eff}}$. As a result, light metals are preferable to be served as the bottom electrode and large acoustic impedance metals are suitable for the IDTs to ensure a large $k^{2}_{\text{eff}}$.

IV. ELECTRODE THICKNESSES

Fig. 5 presents the contour plot of the $k^{2}_{\text{eff}}$ of the S0 mode AlN Lamb wave resonators with different Pt IDT electrode thicknesses for the single-IDT electrode configuration.
Pt gives more reflection, enhancing the electro-mechanical transduction, but the non-piezoelectric and heavy layer loads the transduction when the Pt bottom electrode layer becomes too thick.

It can also be noticed that when the AlN plate is relatively thin ($h_{\text{AlN}}/\lambda < 0.2$), the thicker electrodes decrease the $k_{\text{eff}}^2$, but when the AlN plate is thick ($h_{\text{AlN}}/\lambda > 0.5$), the thicker Pt enhance the $k_{\text{eff}}^2$. The reason is that when the AlN plate is relatively thin, the thicker metal deviates the acoustic wave field more from the piezoelectric layer and thus reduces the electro-mechanical transduction efficiency. However, while the AlN plate is relatively thick, the thicker metal offers stronger stiffening effect and reflection of the acoustic waves that enhances the $k_{\text{eff}}^2$.

V. IDT DUTY FACTOR

All the prior results presented in above sections are simulated with the duty factor of 0.5 ($DF = 0.5$). However, similar to SAW resonators, the change on DF can also affect the $k_{\text{eff}}^2$ of the AlN LWRs. Fig. 6 presents the $k_{\text{eff}}^2$ of the AlN LWRs with different IDT $DF$s for the double-IDT electrode configuration and $h_{\text{metal}} = 0.02\lambda$. For most metal materials including W, Pt, Mo, Ti and Al, the $k_{\text{eff}}^2$ of the AlN LWRs maximizes at a DF of 0.55. For Au and Cu, the $k_{\text{eff}}^2$ of the AlN LWRs reaches the maximal value when the $DF$ is equal to ~0.45 and ~0.5, respectively. Similar to the balance between reactivity and mechanical loading, a larger $DF$ enhances the reactivity which loads the piezo transduction. For the heavy and soft materials like Au and Cu, the loading effects happen earlier as their low phase velocity nature destroys the wave field concentration in the piezoelectric film in spite of the enhanced reactivity due to the large density.

VI. CONCLUSION

The selection of the transducer and bottom electrode configuration, materials, thicknesses and IDT $DF$ has large impact on the performance of AlN Lamb wave resonators, especially on the electromechanical coupling coefficient. For the first time, this study adopts the FEA method to investigate the full conditions and influence of electrodes on the AlN Lamb wave resonators using the $S_0$ mode. Four types of electrode configurations for the AlN LWRs are compared here. For each electrode configuration, the impact of eight metal materials with thicknesses varying from 0 to 0.08 on the effective coupling coefficients are calculated and analyzed. Careful design of the transducer and bottom electrodes can boost the $k_{\text{eff}}^2$ of the AlN Lamb wave resonator from ~2% to ~7%. The results in this paper lay the foundation for the design principles of piezoelectric Lamb wave resonators.

REFERENCES


Fig. 6. FEA simulations of the $k_{\text{eff}}^2$ of AlN Lamb wave resonators with different IDT duty factors for the double-IDT electrode configuration.


