$Sc_{0.15}Al_{0.85}N$-based 4 GHz Coupled Bulk Acoustic Resonators (CBAR) and Filters for the Single-Chip Duplexer Solution

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Abstract— **In this work, a design of BAW-like thin film resonator is presented and demonstrated with 15% Sc doped AlN piezoelectric material. Utilizing the thickness mode coupled with laterally propagated mode, the proposed coupled bulk acoustic resonator (CBAR) is able to achieve over 4 GHz resonant frequency with 400MHz lithographic tunability and a high effective coupling coefficient over 20%. Filters consisting of the proposed CBARs with different electrode pitches are fabricated on a single-chip. Measurement results show that two discrete filters can operate at 3.85GHz and 4.15GHz with 155MHz and 197MHz bandwidth, respectively. With the same material stack and adjacent operating frequency, these filters provide a promising single-chip duplexer solution for the high frequency filtering applications.**

Keywords—ScAlN, bulk acoustic wave, resonator, filter, duplexer

I. INTRODUCTION

Enabled by the acoustic wave filters with features such as low insertion loss and the steep roll off [1], the mobile wireless communication technology is dramatically developing and the frequency spectrum has been extended to over 5GHz. With respect to the category, the surface acoustic wave (SAW) technology is dominating the low frequency band (<2 GHz) market while the bulk acoustic wave (BAW) is the mainstream technology in the high frequency (>2 GHz) filters [2-3]. The main drawback of the BAW technology is that the working frequency of the BAW resonators is dependent on the physical thickness of the whole stack, thus the tuning of the frequency can only be achieved by wafer trimming or adding another layer as mass loading. This hinders the integration of multiple filters for different filtering bands on a single-chip.

To overcome the aforementioned frequency limitation, research efforts have been devoted to resonators design with lithographic frequency tunability. For example, C. Cassella et al. presented a two-dimensional-mode resonator (2DMR) with resonance mode in both thickness and lateral direction and tunable resonant frequency ranging from 720 MHz to 820 MHz [4]. C. Sun et al. demonstrated a Lamb-wave resonator with checker patterning top electrode to achieve various resonant frequencies on a single chip [5]. Y. Zhu et al. presented the laterally coupled alternating thickness (LCAT) mode resonators with working frequency ranging from 2.05 GHz to 2.2 GHz [6]. X. Zhao et al. presented a new resonator design labeled as two-dimensional-resonant rods (2DRRs) with around 0.1 GHz tunable range [7].

However, the effective coupling coefficient (k^2_{eff}) of the aforementioned resonators, whose frequency can be tuned by adjusting the pitch of electrode, is usually limited (<8%) that can hardly meet the requirement in terms of the filter bandwidth, especially for high frequency bands [4-7]. Sc doped AlN has been acknowledged as a promising piezoelectric material to address the k^2_{eff} challenge because of the high longitudinal piezoelectric constant [8-9]. Reported by N. Wang et al., the k^2_{eff} can be improved to over 10% for the LCAT resonators by employing 12% Sc doped AlN [10].

In this work, BAW-like thin film resonators are designed and then demonstrated with 15% Sc doped AlN, to overcome the challenges mentioned above. Labeled as double-patterned coupled bulk acoustic resonator (CBAR), this design concept couple the thickness mode with the laterally propagated mode, thus the resonant frequency is determined by both stack thickness and the pitch of the electrode fingers. By adjusting the pitch from 0.6 μm to 1.6 μm, the frequency tunable range is from 3.6 GHz to over 4 GHz. Measurement results show that over 20% effective coupling coefficient can be achieved. The ladder-type filters consisting of the proposed coupled bulk acoustic resonators are fabricated and measured. The bandwidth of the fabricated filters is measured to be over 150 MHz with filtering band at around 4 GHz. With same film stack and adjacent passbands, filters fabricated on the same wafer provide a low cost single-chip duplexer solution. These features render the proposed resonator design as a competitive candidate for the high band filtering applications.

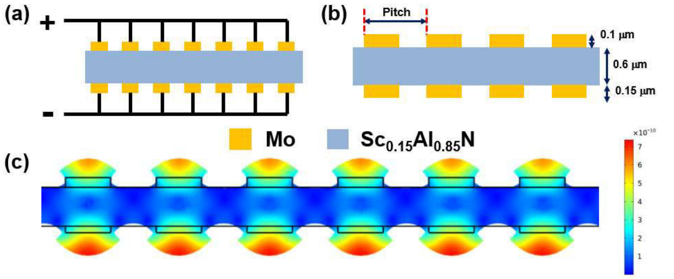

Figure. 1 (a) The schematic cross-section of the double-patterned CBAR; (b) The stack thickness of the CBAR for simulation and fabrication in this work; (c) The resonance mode shape of the double-patterned CBAR.

II. DEVICE MODELING AND DESIGN

As shown in Fig. 1(a), in the proposed double-patterned CBAR, the piezoelectric layer is sandwiched between two comb-shape patterned electrode layers. The electrode fingers at each layer are electrically connected through a bus bar and the signals with opposite polarities are applied on top and bottom electrodes. The film stack in this work for both simulation and fabrication is shown in Fig. 1(b). Electrode pitch is defined as the length of the smallest periodic structure including a finger and an interval. The top electrode is Mo with 0.1 μm thickness, the piezoelectric layer is $Sc_{0.15}Al_{0.85}N$ with 0.6 μm thickness and the bottom electrode is Mo with 0.15 μm. In this double-patterned CBAR, the main resonance mode is the longitudinal thickness mode coupled with the laterally propagated transverse wave, whose adjacent wave peaks locate at the adjacent electrode fingers. The mode shape of the main resonance is shown in Fig. 1(c). Though the cross-section is very similar to the 2DMR proposed by C. Cassella [4], the key difference is that the electrode pitch of CBAR is designed to be close to the wave length of the transverse wave at the resonant frequency of the thickness mode. In this work, with the aforementioned stack thickness, the resonant frequency is around 4 GHz and the pitch of the electrode is from 0.4 μm to 1.6 μm.

To study the dependence of the resonator performance on the electrode pitch, 2-dimentional FEM simulations are conducted using COMSOL. Simulated impedance responses of the proposed CBAR with various electrode pitches are shown in Fig. 2(a). Besides the main mode, other order lateral modes resonance can also be observed in the frequency spectrum as spurious modes. The position of this kind spurious mode is also dependent on the electrode pitch. The dependence of the resonant frequency and k^2_{eff} on the electrode pitch is summarized in Fig.2 (b). The k^2_{eff} is calculated by the equation (1) below:

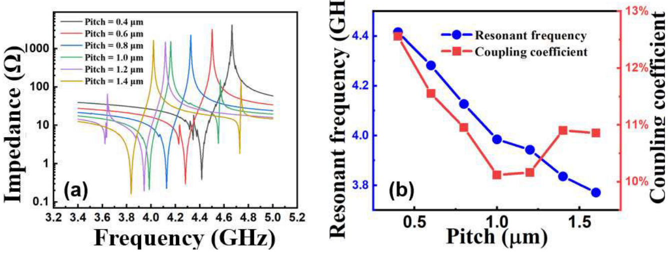

Figure. 2 (a) Simulated impedance response of the $Sc_{0.15}Al_{0.85}N$-based double-patterned CBAR resonators with various electrode pitches; (b) The simulated resonant frequency and the effective coupling coefficient of the simulated double-patterned CBAR resonators with various electrode pitches.

$$k_{eff}^2 = \frac{\theta}{tan\theta}\ ,\theta = \frac{\pi}{2}\frac{f_p}{f_s} \tag{1}$$

where f_s is the series resonant frequency, and f_p is the parallel resonant frequency. With pitch increasing from 0.4 μm to 1.4 μm, the simulated k^2_{eff} first decreases then increases. That is because with increasing pitch, the lateral resonance mode coupled with the thickness mode turns to the next order mode with λ equals to half of the pitch. Within the range λ < pitch < 2* λ, the thickness mode is not fully coupled with any lateral mode, leading to the degradation of the k^2_{eff}.

III. FABRICATION AND CHARACTERIZATION

Fabrication of the filters and resonators are conducted on the in-house 200 mm piezoelectric platform which has been reported in reference [10-11].

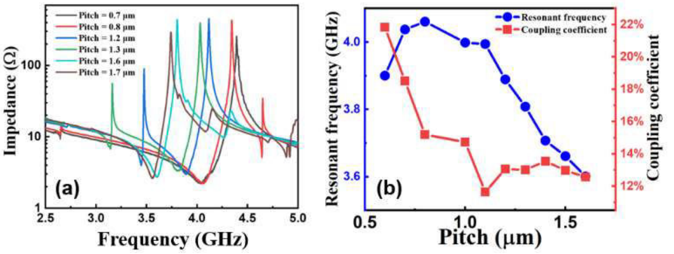

Figure. 3 (a) Measured impedance response of the $Sc_{0.15}Al_{0.85}N$-based double-patterned CBAR resonators with selected electrode pitches; (b) The measured resonant frequency and the k^2_{eff} of the simulated double-patterned CBAR resonators with various electrode pitches.

Electrical testing of the fabricated resonators and filters are performed in the FormFactor CM300xi 300 mm semi-automated shielded probe system with a Keysight N5244B PNA-X Microwave Network Analyzer. 2-port 50 Ω loaded S-parameter is measured with GSG configuration surrounding the device. The capacitance between the ground and signal ports has been mathematically de-embedded to obtain the impedance plots of the resonators. The impedance versus frequency curves of the resonators with selected electrode pitches are plotted in Fig. 3(a). The difference of the impedance response between the measurement and the simulation may be due to the collapse of the piezoelectric layer between adjacent comb fingers, as shown in Fig. 4(a). The extracted f_s and derived k^2_{eff} are summarized in Fig. 3(b). The tunable frequency range of the fabricated double-patterned CBAR is around 400 MHz (3.6 GHz to 4.0 GHz) and the maximum achieved k^2_{eff} can be over 20% with pitch equals to 0.6 μm. The minimum k^2_{eff} is around 12%. Also, the trend of the k^2_{eff} with increasing electrode pitch is consistent with the simulation results.

Ladder-type filters composing the proposed CBAR are fabricated on the same wafer. The topology of the filters is shown in Fig. 4(b). The microscope photos of the fabricated

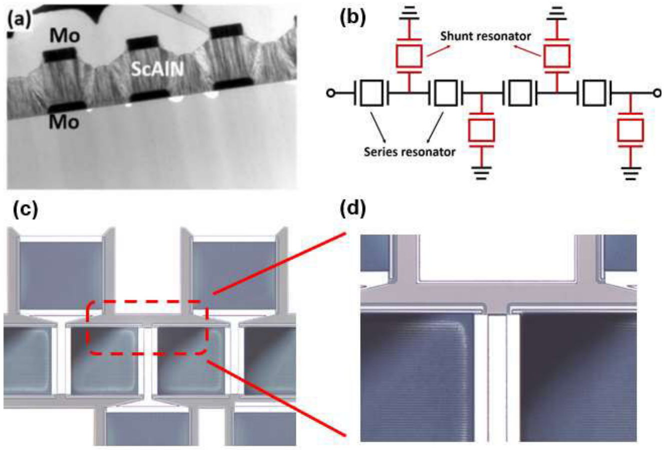

Figure. 4 (a) TEM photo of the resonators with similar double-patterned finger electrode configuration using the same process flow in ref [13]. This figure is cited with permission. (b) The topology of the designed ladder-type filters. (c) The top view of the fabricated ladder filter and (d) the zoomed view to show the top electrode comb fingers.

Table.1 Parameters of the resonators and filters for duplexer

	Shunt Pitch (μm)	Series Pitch (μm)	Max Insertion loss (dB)	Bandwidth (Max-3dB) (MHz)
Low freq. filter	1.22	1.2	3.60	155
High freq. filter	1.22	0.8	3.06	191

filters are shown in Fig. 4(c) & (d). For the ladder-type filter, the f_p of the shunt resonator should be slightly lower than the f_s of the series resonator. Thus for each filter, the electrode pitch of the series resonator is designed to be smaller than the pitch of the shunt resonator. The filter with low frequency band consists of four shunt resonators with pitch = 1.22 μm and four series resonators with pitch = 1.20 μm, while the filter with high frequency band consists of four shunt resonators with pitch = 1.22 μm and four series resonators with pitch = 0.8 μm. Measured insertion loss (S21) is illustrated in Fig. 5(a) and the in-band transmission response is shown in Fig. 5(b). The design and derived performance parameters of the two filters are summarized in Table.1. Centered at 3.85 GHz and 4.05 GHz, the passband of the two filters locates close to each other. Due to the impedance mismatch, the maximum insertion loss within the passband is 3.60 dB and 3.06 dB, respectively. The bandwidth is calculated to be 155 MHz and 191 MHz, using the max - 3 dB insertion loss as the band edge. The out-of-band rejection of both filters is around 25 dB and no ripples are observed inside the passbands. With the high bandwidth and the lithographic frequency tunability, the proposed CBAR and the CBAR-based filters are promising for the duplexer applications. Further optimization of the Q-factor of the resonator is needed to improve the insertion loss and the roll off of the filters.

IV. CONCLUSION

This paper reports a BAW-like resonator design with comb-shape electrode layers for lithographic frequency tunability. Demonstrated with 15% Sc doped AlN, the frequency tunable range of the proposed resonator is from 3.6 GHz to over 4 GHz with k^2_{eff} up to 20%. The resonators are implemented in the ladder-type filters with adjacent passbands. Benefiting from the high k^2_{eff}, over 150 MHz bandwidth is achieved with filtering band at around 4 GHz. This resonator design provides a promising single-chip duplexer solution.

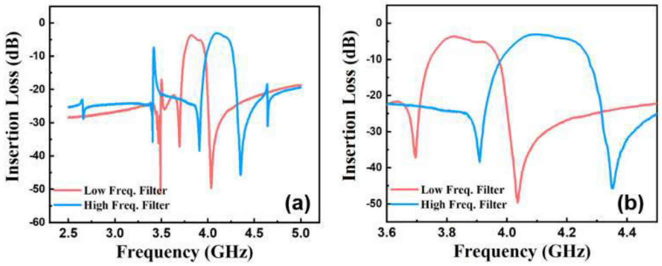

Figure. 5 (a) Measured insertion loss of the fabricated filters around 4 GHz for duplexer applications. (b) The in-band characteristics of the fabricated filters.

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REFERENCES

[1] F. Z. Bi and B. P. Barber, “Bulk acoustic wave RF technology,” IEEE Microw. Mag., vol. 9, no. 5, pp. 65–80, 2008.

[2] R. Aigner, G. Fattinger, M. Schaefer, K. Karnati, R. Rothemund, and F. Dumont, “BAW Filters for 5G Bands,” Tech. Dig. - Int. Electron Devices Meet. IEDM, vol. 2018-Decem, pp. 14.5.1-14.5.4, 2019.

[3] R. Ruby, “A snapshot in time: The future in filters for cell phones,” IEEE Microw. Mag., vol. 16, no. 7, pp. 46–59, Aug. 2015

[4] C. Cassella and G. Piazza, “AlN Two-Dimensional-Mode Resonators for Ultra-High Frequency Applications”, IEEE Electron Device Letter, vol. 36, No. 11, Nov. 2015

[5] C. Sun, B. W. Soon, Y. Zhu, N. Wang, P. H. Loke, X. Mu, J. Tao, and Y. Gu, “Methods for improving electromechanical coupling coefficient in two dimensional electric field excited AlN Lamb wave resonators,” Appl. Phys. Lett., vol. 106, p. 253502, Jun. 2015.

[6] Y. Zhu, N. Wang, G. Chua, C. Sun, N. Singh and Y. Gu, “ScAlN-Based LCAT Mode Resonators Above 2 GHz With High FOM and Reduced Fabrication Complexity”, IEEE Electron Device Letter, vol. 38, No. 10, Oct. 2018

[7] X. Zhao, L. Colombo, and C. Cassella, “Aluminum nitride two-dimensionalresonant-rods”, Appl. Phys. Lett. 116, 143504 (2020);

[8] M. Akiyama, T. Kamohara, K. Kano, A. Teshigahara, Y. Takeuchi and N. Kawahara, “Enhancement of piezoelectric response in scandium aluminum nitride alloy thin films prepared by dual reactive cosputtering”, Advanced Materials, 21(5), 593–596, 2009

[9] N. Kurz, F. Parsapour, V. Pashchenko, L. Kirste, V. Lebedev, P. Muralt, O. Ambacher and N. Pascal, “Determination of Elastic and Piezoelectric Properties of $Al_{0.84}Sc_{0.16}N$ Thin Films”, IEEE International Ultrasonics Symposium, IUS, 2018-Octob, 1–5, 2018

[10] N. Wang, et al., "Over 10% of k^2_{eff} Demonstrated by 2-GHz Spurious Mode-Free $Sc_{0.12}Al_{0.88}N$ Laterally Coupled Alternating Thickness Mode Resonators," IEEE Electron Device Letters, vol. 40, pp. 957-960, 2019.

[11] Y. Zhu, et al., "A High Coupling Coefficient 2.3-GHz AlN Resonator for High Band LTE Filtering Application," IEEE Electron Device Letters, vol. 37, pp. 1344- 1346, 2016