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Over 12% of Coupling Coefficient Demonstrated by 3GHz $Sc_{0.12}Al_{0.88}N$ Based Laterally Coupled Alternating Thickness (LCAT) Mode Resonators

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***Abstract*— In this work, we report a laterally coupled alternating thickness (LCAT) mode resonators operating at 3GHz with an effective electromechanical coupling coefficient (k^2_{eff}) of 12.1%, using 12% scandium-doped aluminum nitride ($Sc_{0.12}Al_{0.88}N$) as the piezoelectric layer. The top and bottom electrodes are formed by patterning two groups of interdigitated electrodes (IDEs) on the top and bottom surface of the $Sc_{0.12}Al_{0.88}N$ layer, respectively, both made of molybdenum (Mo). The thickness of the top electrode layer, $Sc_{0.12}Al_{0.88}N$ layer, and the bottom electrode layer is 0.1µm, 0.7µm, and 0.2µm, respectively. The designed resonator is fabricated by in-house 200mm piezoelectric platform, with the $Sc_{0.12}Al_{0.88}N$ deposited by physical vapour deposition (PVD). Electrical measurement results show that the series resonant frequency (f_s) and the parallel resonant frequency (f_p) are 2.96 GHz and 3.10 GHz, respectively, and the corresponding impedance at f_s (R_s) and impedance at f_p (R_p) are 3.19 Ω and 546 Ω, respectively. Besides the high k^2_{eff} of 12.1%, no spurious resonant modes are observed within a wide 1.2GHz frequency spectrum, demonstrating great potential of the reported $Sc_{0.12}Al_{0.88}N$ based LCAT mode resonator in 5G duplexing solution on a single chip.**

Keywords*— *scandium-doped aluminum nitride, ScAlN, LCAT, resonator, spurious mode, coupling coefficient, high frequency

I. Introduction

Over the past two decades, research interest on micro-electro-mechanical-system (MEMS) resonators based on aluminium nitride (AlN) for radio-frequency (RF) wireless communication has received an unprecedented growth, thanks to the complementary-metal-oxide-semiconductor (CMOS) compatibility of AlN which makes the integration of filters into the RF front-end solution feasible [1, 2]. As surface acoustic wave (SAW) technology has limitations in applications of high-band filtering, aluminium nitride (AlN) based bulk acoustic wave (BAW) technology is currently dominating the high-band filtering market[3].

However, with the advancement in the current 4G technology such as multiple-input-multiple-output (MIMO) and carrier aggregation (CA), as well as in light of the 5G era, the number of filters which are going to be packed into the same area will be tremendously increased. Therefore, the nature of film-stack-dependent operating frequency of BAW technology will post great challenge to the current heterogeneous duplexing solution, whereby a significant portion of the board area is occupied by the wirebonding which connects the filters serving different bands. Therefore, a solution which can reduce the unutilized board area is needed.

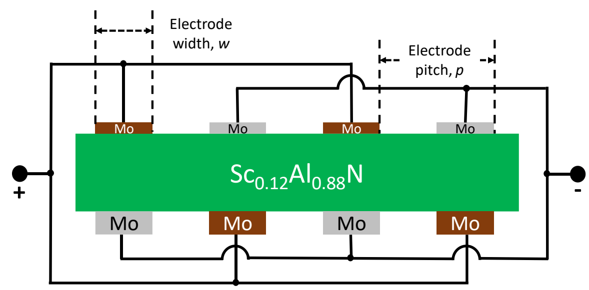

Figure 1: Illustration of the cross section of the LCAT mode resonator. The top and bottom electrodes are formed by patterning two groups of interdigitated electrodes (IDEs) on the top and bottom surface of the $Sc_{0.12}Al_{0.88}N$ layer, respectively, both made of molybdenum (Mo). The thickness of the top electrode layer, $Sc_{0.12}Al_{0.88}N$ layer, and the bottom electrode layer is 0.1µm, 0.7µm, and 0.2µm, respectively. The definition of electrode width (w), electrode pitch (p), and the IDE connection scheme are also illustrated.

Lamb wave resonators are one of the solutions which can potentially overcome the aforementioned challenge, due to its lithographically tuned resonant frequency which enables the feasibility of integrating filters with different frequency onto the same chip [4-8]. However, the performance of this type of resonators, especially the effective electromechanical coupling coefficient (k^2_{eff}) which determines the bandwidth of the filters constructed, is not as high as that of BAW technology.

Therefore, researchers started to focus on improving the performance, especially the k^2_{eff}, of Lamb wave resonators, by optimizing the design, such as employing checker-patterned top metal electrode to excite lateral Lamb waves along two dimension [9] and combining one-dimension lateral mode with thickness mode[10-15], or adopting scandium (Sc) doping in AlN (ScAlN) [16, 17], or both[18, 19]. These methods are

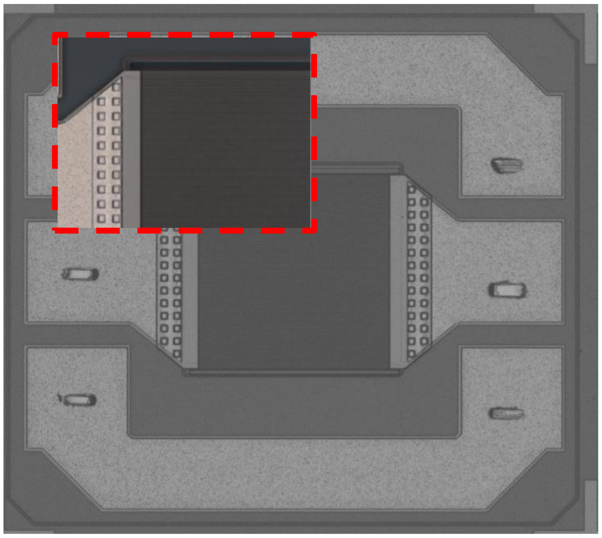

Figure 2: Scanning electron microscope (SEM) micrograph of the fabricated LCAT mode resonator reported in this work. The width of the electrode finger (w) and electrode pitch (p) of both top and bottom IDE fingers are designed to be 0.72µm and 1.20µm, respectively. Zoom-in view of the IDE fingers is depicted in the inset.

proved to be capable of improving the k^2_{eff} while maintaining the capability of lithographically tuned operating frequency.

In International Ultrasonic Symposium (IUS) 2018, we have already reported the feasibility of single-chip duplexing solution by two AlN based Laterally Coupled Alternating Thickness (LCAT) mode filters, which are fabricated on the same wafer, delivering two adjacent frequency bands around 2.4GHz[20]. In this work, we report a $Sc_{0.12}Al_{0.88}N$ based LCAT mode resonator operating at 3GHz range, demonstrating great potential in 5G duplexing solution on a single chip.

II. Resonator Design

Figure 1 iillustrates the cross section of the LCAT mode resonator. The $Sc_{0.12}Al_{0.88}N$ based LCAT mode resonator reported in this work comprises of a 0.7µm-thick ScAlN layer, where 12% a.t. of Sc is doped into AlN film. The top and bottom electrodes are formed by patterning two groups of interdigitated electrodes (IDEs) on the top and bottom surface of the $Sc_{0.12}Al_{0.88}N$ layer, respectively, both made of molybdenum (Mo). The thickness of the top electrode layer and the bottom electrode layer is 0.1µm and 0.2µm, respectively. The width of the electrode finger (w) and electrode pitch (p) are designed to be 0.72µm and 1.20µm, respectively. Also shown in Figure 1 is the way which electrical signals are applied to the two groups of top IDEs and the two groups of bottom IDEs. With such configuration, the signals applied to the top IDE and the bottom IDE at the same lateral position is of the opposite polarity, which is capable of exciting a thickness mode; the signal applied to the two adjacent IDE on the same side of the $Sc_{0.12}Al_{0.88}N$ layer is also of the opposite polarity, which is capable of exciting a lateral mode. It is to be noted that the thickness modes excited by the two adjacent pairs of top/bottom IDEs are opposite in phase, thus termed alternating thickness (AT) mode. As such, the AT mode excited by the top and bottom IDE pair can then be synergically coupled by the lateral mode excited by the adjacent electrode pair, enhancing the k^2_{eff}.

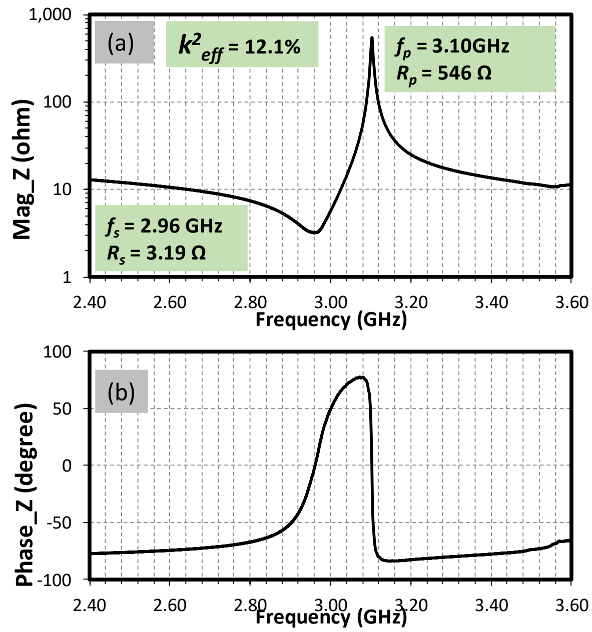

Figure 3: Measured frequency response of impedance, (a) Magnitude (Z_Mag). (b) Phase (Z_Phase), of the fabricated $Sc_{0.12}Al_{0.88}N$ based LCAT mode resonators. The series resonant frequency (f_s) and the parallel resonant frequency (f_p) are 2.96 GHz and 3.10 GHz, respectively, and the corresponding impedance at f_s (R_s) and the impedance at f_p (R_p) are 3.19 Ω and 546 Ω, respectively. The effective coupling coefficient (k^2_{eff}) of 12.1% can then be extracted.

III. Fabrication Process

The proposed LCAT mode resonator is fabricated by the in-house 200mm piezoelectric platform, in which the $Sc_{0.12}Al_{0.88}N$ film is deposited by physical vapour deposition (PVD), DC magnetron sputtering of a $Sc_{0.12}Al_{0.88}$ target in particular. The integration process to fabricate the proposed LCAT mode resonator is similar to the process which has been reported in our previous work [10], but tuning and optimization has to be made in order to address the difference in physical and chemical properties of AlN film reported in our previous work and $Sc_{0.12}Al_{0.88}N$ film which is reported in this work. Firstly, in order to achieve higher resonant frequency at 3GHz, the $Sc_{0.12}Al_{0.88}N$ has to be thinner than that 1µm reported previously [19]. This requires fine tuning to ensure the film quality as the film quality, in particular the full width at half maximum (FWHM) of X-ray diffraction (XRD) rocking curve, gets better for thicker film. Secondly, although ScAlN film can also be etched using chlorine chemistry as that of AlN film, the etch rate, as well as etching selectivity against silicon dioxide (SiO_2), for ScAlN is much lower than that for AlN. Therefore, the thickness of the SiO_2 hardmask has to be thicker, making the definition of smaller feature more challenging. Figure 2 shows the scanning electron microscope (SEM) micrograph of the fabricated LCAT mode resonator reported in this work. The width of the electrode finger (w) and electrode pitch (p) of both top and bottom IDE fingers are designed to be 0.72μm and 1.20μm, respectively. Zoom-in view of the IDE fingers is depicted in the inset.

IV. RESULTS AND DISCUSSIOINS

A short-open-load-through (SOLT) calibrated Keysight N5242B two-port vector network analyzer (VNA) is used to carry out the electrical characterization of the fabricated LCAT mode resonator, by directly connecting the the "+" and "-" terminals of the resonator (Figure 1) to the two 50Ω terminations of the VNA. The scattering (S) parameters of the two-port network directly obtained from the VNA without any de-embedding structure is then used to extract the impedance of the resonator. Electrical measurement results show that the series resonant frequency (f_s) and the parallel resonant frequency (f_p) are 2.96 GHz and 3.10 GHz, respectively, and the corresponding impedance at f_s (R_s) and impedance at f_p (R_p) are 3.19 Ω and 546 Ω, respectively. The k^2_{eff} of 12.1% can then be extracted, which is among the highest obtained for CMOS compatible AlN based resonator with lithographically tunable resonant frequency. Therefore, the reported LCAT mode resonator is a very promising candidate in next-generation RF communication applications.

V. CONCLUSIONS

In this work, a LCAT mode resonators operating at 3GHz with a k^2_{eff} of 12.1% is reported. The piezoelectric layer is 0.7μm-thick $Sc_{0.12}Al_{0.88}N$, whereas the top and bottom electrodes are formed by patterning two groups of Mo IDEs with a thickness of 0.1μm on the top surface of the $Sc_{0.12}Al_{0.88}N$ layer and another two groups of Mo IDEs with a thickness of 0.2μm on the bottom surface of the $Sc_{0.12}Al_{0.88}N$ layer, respectively. The designed resonator is fabricated by in-house 200mm piezoelectric platform, with PVD used to deposit the $Sc_{0.12}Al_{0.88}N$ film. Electrical measurement results show that f_s and f_p are 2.96 GHz and 3.10 GHz, respectively, whereas R_s and R_p are 3.19 Ω and 546 Ω, respectively. Besides the high k^2_{eff} of 12.1%, no spurious resonant modes are observed within a wide 1.2GHz frequency spectrum, demonstrating great potential of the reported $Sc_{0.12}Al_{0.88}N$ based LCAT mode resonator in 5G duplexing solution on a single chip.

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