Top Metal Coverage Impact on the Performance of Thin-Film Piezoelectric-on-Substrate Resonators

Parvin Akhkandi, Reza Abdolvand
Department of Electrical and Computer Engineering
University of Central Florida
Orlando, Florida, USA
parvin.akhkandi@knights.ucf.edu

***Abstract*— In this paper, the effect of top electrode design on the electromechanical coupling coefficient (k_t^2) and the quality factor (Q) of lateral bulk-acoustic thin-film piezoelectric-on-substrate (TPoS) MEMS resonators is studied. Several TPoS resonators with various top electrode coverage ranging from 40% to 86% fabricated at a center frequency of 25 MHz. The resonators with 60% top electrode coverage exhibit improved Figure of Merit (FOM), defined as the product of electromechanical coupling coefficient (k_t^2) and quality factor (Q) compared to both higher and lower coverage. Our finding suggests that by careful optimization of the top electrodes we can significantly improve the performance of systems that utilize such resonators.**

Keywords—TPoS; MEMS resonators; quality factor; electromechanical coupling;

I. Introduction

Microelectromechanical systems (MEMS) are considered a promising alternative to quartz crystals in RF front end, and sensors applications due to their small footprint, low power consumption, CMOS technology compatibility. Two important parameters in evaluating MEMS resonators are electromechanical coupling coefficient, k_t^2 and, quality factor, Q.

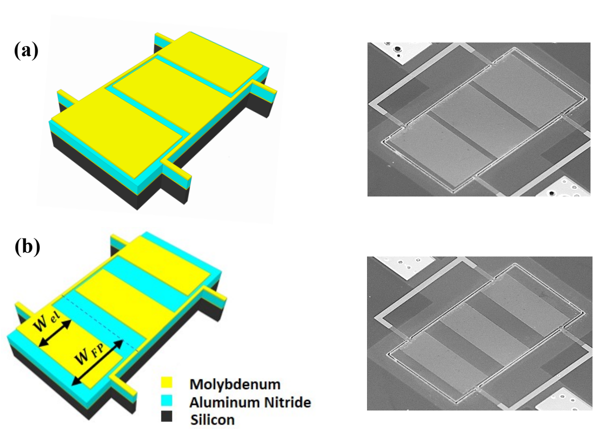
In designing resonant systems, achieving high quality factor (Q) along with a large electromechanical coupling (k_t^2) typically results in higher performance. Consequently, a figure of merit (FoM) that is used for characterization of MEMS resonator is $k_t^2.Q$ [1].

In this work, we experimentally explore how the top electrode geometry in thin-film piezoelectric-on-silicon lateral bulk-extensional MEMS resonators impacts the FOM. Previous studies have revealed the effect of various electrode designs on the MEMS resonators' electromechanical properties [2-4]. The impact of the electrodes in TPoS MEMS resonators on FoM is yet to be reported. Based on the theory of interfacial losses, reducing the metal coverage area in MEMS resonators is expected to result in higher Q. On the other hand, reducing metal coverage would result in lower k_t^2. In this paper, we have designed and fabricated three different top electrode configurations at the center frequency of 25 MHz in 3rd and 5th harmonic order resonators. A total of 18 devices have been tested using the impedance response measurement setup. This work outlines the experimental analysis, and in-depth discussion of the significant findings of the effort.

II. Design and Fabrication

Multiple TPoS resonators operating in bulk lateral extensional mode were fabricated at the designed center frequency of ~25Mhz to study the impact of the top electrode design on the FOM of TPoS MEMS resonators. The devices were fabricated in the <110> silicon crystalline orientation on the same highly N-doped 16um silicon-on-insulator (SOI) substrate. In these resonators, a thin layer of Aluminum-Scandium-Nitride ($Al_{0.84}Sc_{0.16}N$) is sandwiched between a bottom metal plate and a patterned top electrode (~100 nm of Molybdenum) stacked on a low acoustic loss single-crystalline Silicon substrate layer.

As illustrated in Figure 1, the top electrode coverage ratio is defined as the ratio of the electrode width over half the resonance frequency wavelength (i.e., finger pitch). The resonators with converge ratio of 40%, 60%, and 85% were fabricated, and their $FoM = Q \times k_t^2$ was characterized. Careful consideration was given to ensure that all other design and fabrication parameters were identical across the resonators. The schematic and Scanning Electron Microscopy (SEM) images of a set of 3rd harmonic order resonators is depicted in Figure 1.



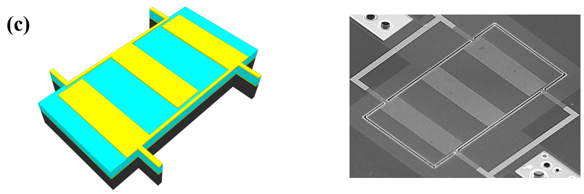


Figure 1. (a) Schematic diagram (left) and Scanning Electron Microscopy (SEM) micrograph (right) of 85% top electrode coverage. (b) Schematic diagram (left) and Scanning Electron Microscopy (SEM) micrograph of 60% top electrode coverage. (c) Schematic diagram (left) and Scanning Electron Microscopy (SEM) micrograph of 40% top electrode coverage.

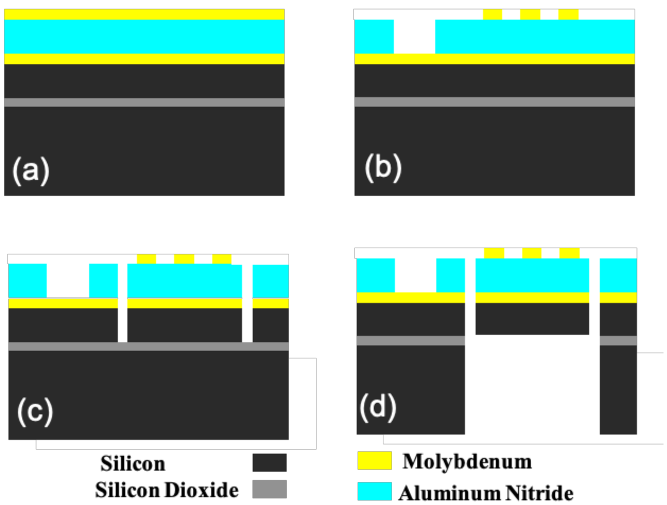


Figure 2. The simplified schematic process flow for fabricating TPoS MEMS resonators.

The TPoS MEMS resonators were fabricated on a relatively thick (16 um) degenerately N-doped [100] SOI substrate in a five-mask process. The 1 um thick sputtered 20%-Scandium doped AlN film is sandwiched between two 100nm thick Molybdenum layers (Figure 2.a).

To create the interdigitated finger pattern that form the top electrodes, the top metal layer is dry etched in SF6 plasma. In order to create electrical access to the bottom metal electrodes the ScAlN thin film is then wet etched (Figure 2.b) by alternatingly submerging the wafer in heated TMAH and Sulfuric acid baths. The etch rate of ScAlN was measured to be 200 nm/min. To improve probe contact, a 30/100-nm stack of Chromium/Gold is deposited on the electrode pads using lift-off technique. The resonator's body is formed by etching trenches using a chlorine-based inductively coupled plasma reactive ion etching (ICP RIE) process for the piezoelectric layer followed by a deep RIE for the Si layer (Figure 2.c). The resonator is finally released by wet etching the box oxide layer in a buffered oxide (BOE) etchant after the handle layer silicon is etched from the backside in a deep-reactive-ion (DRIE) using the Bosch process (Figure 2.d).

III. METHODS AND RESULTS

The loaded quality factor was calculated from the resonators' frequency response as measured by a ZNB-8 Rohde and Schwarz Vector Network Analyzer (VNA) and was converted to unloaded quality factor. The resonators' k_t^2 was calculated using Eqn. 1.

$$k_t^2 = \frac{f_p^2 - f_s^2}{f_p^2} \tag{1}$$

Here, f_s and f_p are the series and parallel resonance frequencies, defined as the maximum and minimum of the resonator's one-port impedance (Z_{11}). The measured Z_{11} plots for three of the tested resonators with different coverage ratios are shown in Figure 3. As expected an increase in coverage ratio resulted in a downward shift of the resonance frequency due to the mechanical loading effect.

Through plotting the quality factor and k_t^2 of the 3rd harmonic order resonators (Figure 4.a) and 5th harmonic order resonators (Figure 4.b) it is observed that for both cases the Q decreases with coverage ratio, whereas k_t^2 increases. As discussed in prior art the coupling factor in the lateral extensional resonators of this work is expected to reach a theoretical maximum at around ~75% electrode coverage assuming both top and bottom electrodes were patterned [5]. Considering this fact, a larger electrode coverage (>85%) is expected to result in a lower coupling factor defeating the optimization purpose.

The FoM for the 3rd and 5th order resonators was plotted in Figure 5. It was observed that across the different harmonic orders, resonators with 60% coverage ratio have the highest FoM. This result illustrates that in the design of TPoS resonators the electrode coverage should be considered as an important parameter to achieve optimal performance.

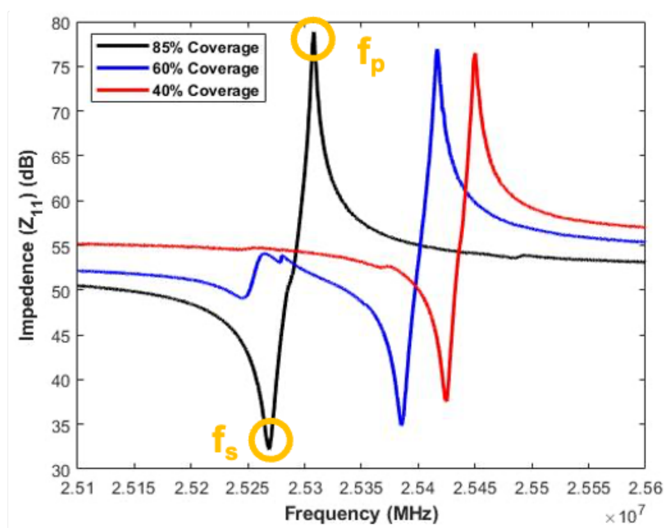
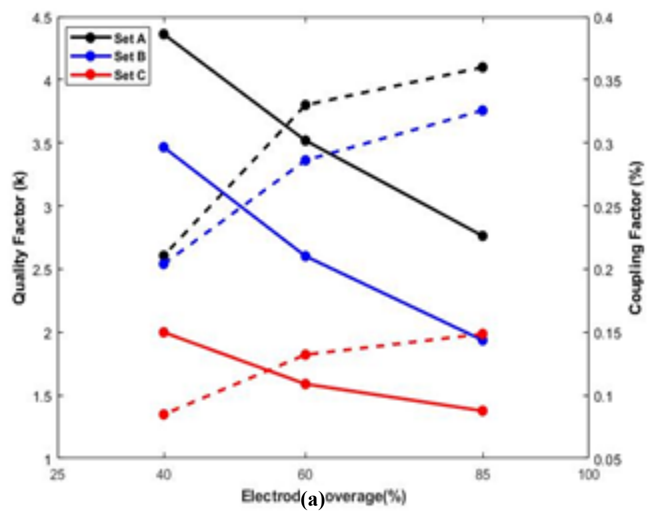
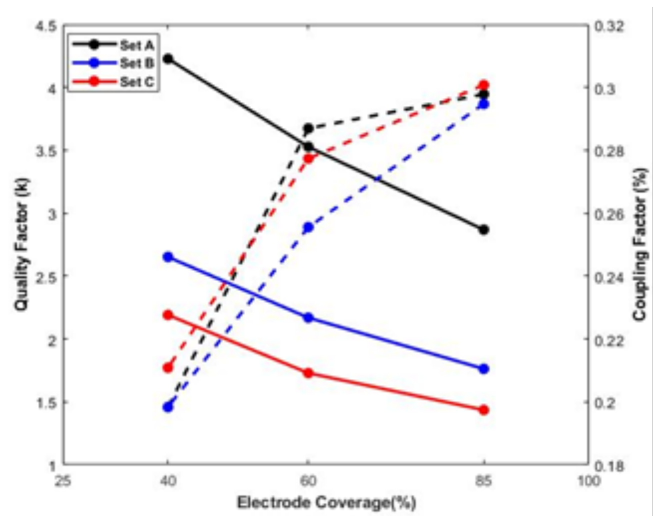


Figure 3. Measured Z_{11} of resonators with three different coverage ratios. The sensitivity of the impedance to coverage ratio can be observed.

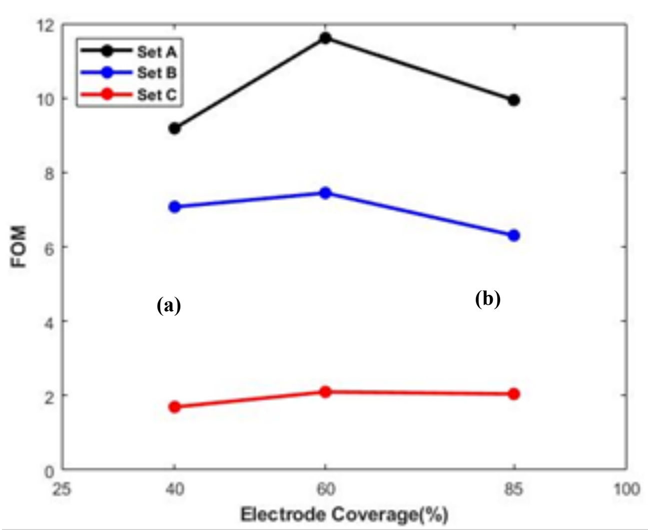


(a)



(b)

Figure 4. (a) Measured Q and k_t^2 of 3rd order TPoS resonators. (b) Measured Q and k_t^2 of 5th order TPoS resonators. Each set consists of a single design with three different coverage ratios.



(a) (b)

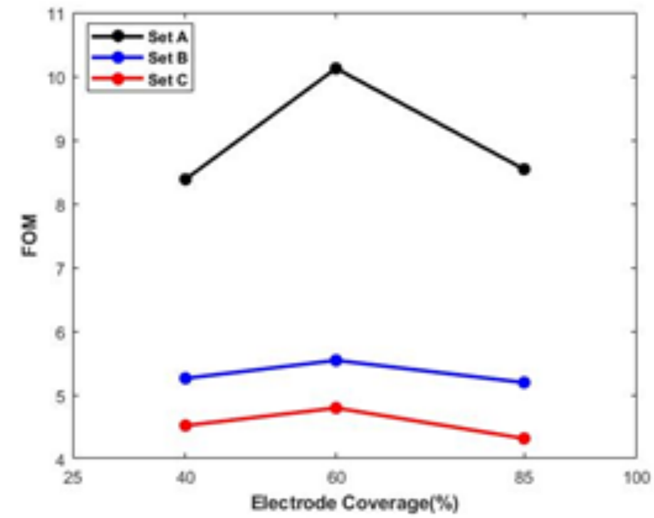


Figure 5. FOM (a product of Q and k_t^2) of (a) 3rd harmonic order and (b) 5th harmonic order TPoS resonators as a function of top electrode coverage ratios.

Following [2], we developed a theoretical framework to gain a better understanding of the measurements shown in Figure 4 and Figure 5. To understand why Q decreases with an increase in coverage, we formulate the resonator's loss in terms of coverage ratio. We know the overall Q of a resonator can be broken down according to the different sources of energy loss:

$$\frac{1}{Q_{tot}} = \frac{1}{Q_{die}} + \frac{1}{Q_{p-p}} + \frac{1}{Q_{air}} + \frac{1}{Q_{ohm}} + \frac{1}{Q_{interface}} + \frac{1}{Q_{other}} \quad (2)$$

Given that the only difference between the resonators for a similar design is coverage ratio, any delta in quality factor must stem from loss source(s) that are a function of coverage ratio. Following [2], we believe that interfacial loss is the only parameter that is directly a function of coverage ratio.

To understand why Q decreases with lower electrode coverage, it is helpful to review the definition of the Q.

$$Q = 2\pi\left(\frac{Stored\ Energy}{Lost\ Energy}\right) \quad (3)$$

As shown in equation 3 the two pathways for increasing quality factor are increasing the stored energy and minimizing the lost energy.

Here, given that the resonators' design is identical except for the top electrode configuration, stored energy cannot vary significantly from design to design. Assuming that a high percentage of the losses is related to interfacial losses, Q is calculated to be inversely proportional to $Loss_{int}$ as

$$Q \propto {}^{1}\!/_{Loss_{int}^{top}} + {}^{1}\!/_{Loss_{int}^{bottom}} \quad (4)$$

The bottom metal layer is identical in all three designs therefore, by making the top electrodes narrower Q is shown to increase meaningfully.

Building on the definition of electromechanical coupling given in (1), for a partially covered electrode plate, k_t^2 can be calculated as [5]:

$$k_t^2 = (\frac{W_{FP}}{W_{EL}}.\sin(f_0\frac{\pi}{2}\frac{W_{EL}}{W_{FP}}))^2 \quad (5)$$

Where W_{FP} is one finger pitch or half of the wavelength and W_{EL} is the electrode width. This equation shows that an increase in coverage ratio (W_{EL}/W_{FP}) results in an increase in coupling factor.

IV. Conclusions

In this study, we report the impact of different top electrode designs on TPoS MEMS resonators' electromechanical properties. Our results indicate that top electrode design affects the quality factor and electromechanical coupling coefficient. Three different top electrode designs were fabricated and measured. The results illustrate that an increase in electrode coverage leads to lower Q and an increase in k_t^2. Therefore, the design of TPoS electrodes' dimensions is not straightforward and necessitates significant optimization efforts to obtain a higher figure of merit.

References

[1] Abdolvand, R., Fatemi, H., & Moradian, S. (2017). Quality factor and coupling in piezoelectric mems resonators. In *Piezoelectric MEMS Resonators* (pp. 133-152). Springer, Cham.

[2] Cassella, C., Segovia-Fernandez, J., & Piazza, G. (2013). Segmented electrode excitation of aluminum nitride contour mode resonators to optimize the device figure of merit. *The 17th International Conference on Solid-State Sensors, Actuators and Microsystems*, 506-509.

[3] Jung, S.I., Piazza, G., & Kim, H.J. (2019). The Impact of Bottom Electrode Coverage Rate on Electromechanical Coupling and Quality Factor of AlN MEMS Contour Mode Resonators. *2019 20th International Conference on Solid-State Sensors, Actuators and Microsystems & Eurosensors*, 917-920.

[4] Jung, S. I., Ryu, C., Piazza, G., & Kim, H. J. (2019). A Study on the Effects of Bottom Electrode Designs on Aluminum Nitride Contour-Mode Resonators. *Micromachines*, *10*(11).

[5] Piazza, G., Stephanou, P., & Pisano, A. (2007). One and Two Port Piezoelectric Higher Order Contour-Mode MEMS Resonators for Mechanical Signal Processing. *Solid-state Electronics, 51*, 1596-1608.