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Boosting the Quality Factor of Low Impedance VHF Piezoelectric-on-Silicon Lateral Mode Resonators using Etch Holes

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Abstract

We report a unique method of using etch-holes to greatly improve the unloaded quality factor (Q_u) of VHF-band low impedance laterally vibrating AlN Thin-film Piezoelectric-on-Silicon (TPoS) MEMS resonators. We have validated the proposed method experimentally by applying it to fabricated devices with resonant frequencies of 105MHz. Based on the experimental results of several fabricated samples, we show that the quality factors of the resonators consistently improve by almost four times using the proposed method. The experimental results are corroborated by finite-element (FE) simulations, which show that the holes re-distribute the strain energy in the resonator and suppress the movement in the supporting beam tethers. Less energy in the tethers leads to reduction of anchor loss and thus enhances Q_u.

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Keywords: Piezoelectric-on-silicon resonators; etch holes; anchor loss.

1. Introduction

TPoS micromechanical resonators have recently drawn increasing attention due to their strong electromechanical coupling, high power handling, and compatibility with CMOS fabrication [1]. So far, TPoS resonators have been used to form integrated high-frequency oscillators [2], radio frequency (RF) filters [3] and low power resonant sensors [4]. In all these applications, high Q is desired. In the case of oscillators, Q sets the close-to-carrier phase noise. In RF filters, higher Q reduces insertion loss in filters while narrowing the bandwidth. In the case of resonant

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sensors, higher Q benefits detection resolution. However, the reported values of Q for TPoS resonators are typically much lower than capacitive silicon resonators at the same frequency range. Anchor loss has been seen as one of the primary sources of energy loss limiting Q in piezoelectric resonators [5]. A number of ad-hoc structures have been proposed to minimize anchor loss in TPoS resonators. Harrington et al [6] showed that Q could be improved by introducing in-plane reflectors placed at a chosen distance away from supporting ethers. Another approach proposed by Zhu et al used 2D phononic-crystal arrays with engineered acoustic band-stop characteristics [7] to reduce anchor loss. The drawback of these methods is that they increase the net device area. This work explores a more compact solution to boost Q via strategic placement of etch holes in the resonator body. Etch-holes are common perforation features when fabricating silicon-on-insulator (SOI) micromechanical resonators to realize free standing structures. We have previously found that uniformly distributed etch holes drastically reduce Q in SOI square-plate resonators by increasing thermoelastic damping (TED) [8]. In this work, we show that when placed strategically, holes can be used to significantly enhance Q in a 105MHz TPoS resonator.

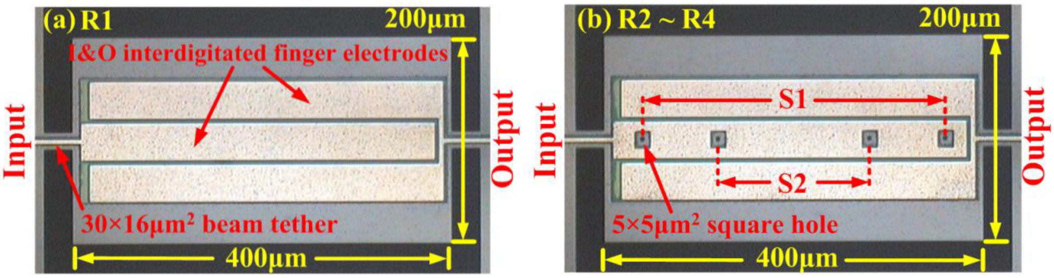


Fig. 1. Optical micrographs of (a) plain TPoS resonator (R1); (b) three variants of TPoS resonators with different hole-spacing: $S1$=280μm, $S2$=32μm (R2); $S1$=320μm, $S2$=130μm (R3); $S1$=320μm, $S2$=160μm (R4).

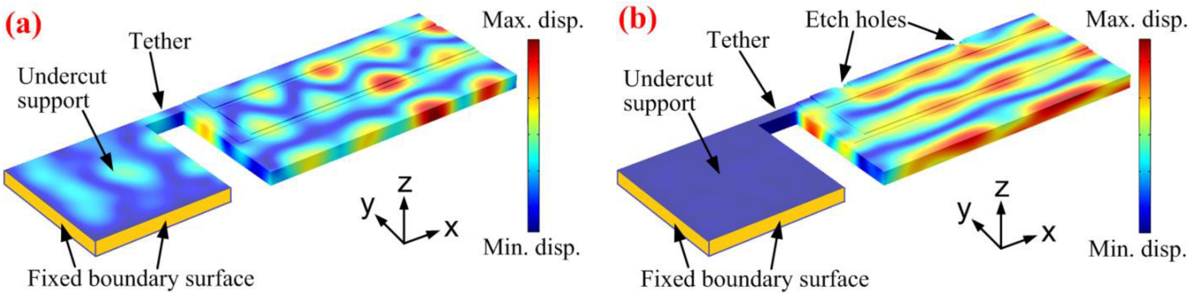


Fig. 2. FE simulated 5th order width-extensional mode shape of a (a) plain TPoS resonator (R1); (b) TPoS resonator with etch holes (R3); the colour-coded contours denote the relative magnitude of displacement.

2. Design and Simulation

We designed four TPoS rectangular-plate resonators (referred to as R1~R4) of the same size and beam supports. As shown in Fig 1, R1 is a conventional width-extensional mode resonator with no holes while R2~R4 contain four 5×5μm^2 square holes along the center line of the resonators. The spacing between the holes (denoted by $S1$ and $S2$) is slightly different between R2~R4 for the purpose of comparison. Fig 2(a) shows the FE eigenfrequency simulation (using COMSOL Multiphysics) of the mode shape for R1. Analysis was performed on a quarter section of the device due to the symmetry of the vibration mode. Fixed boundaries have been applied to the perimeter of the undercut supports along which the entire freestanding structure is anchored to the handling substrate of the SOI wafer. The material properties of the respective layers (Al, AlN and Si layer) adopted in the simulations are the same as those used in [9]. It can be seen in Fig 2(a) that the displacement on the resonator body is not uniform along x-direction. This is because the vibration in the y-direction is accompanied by comparable level of movements in both the x- and z- directions. The x- and z- direction movements are caused by the large Poisson's ratio of the AlN film (~0.3) as well as the differences in the stiffness between the AlN film and the silicon substrate [9]. Given that the tether is a continuum structure that physically links the resonator plate and the undercut support, the x- and z-direction movements are also transferred to the supporting beam tether, thus causing acoustic energy leakage from the resonator body to the undercut support as shown in Fig 2(a). The FE simulated mode shape for R3 is shown in Fig 2(b), where it can be seen that the displacement on the resonator body is more uniform after strategically placing the square holes. Fig 2(b) also shows that the movement on the tether is much smaller compared to that in Fig 2(a). This suggests that the holes serve to redistribute the strain energy in the resonator body and help reduce the acoustic energy loss through the tethers. Suppressions of movement on the tethers were also found for R2 and R4.

3. Measurement and Discussion

The devices were fabricated using a foundry AlN-on-SOI MEMS process. We electrically characterized three die samples of the four designs (i.e. total of 12 devices) in mTorr levels of vacuum in a probe station (Janis Research ST-100). Electrical characterization was carried out using a network analyzer (Agilent E5061A) after performing short-open-through (SOT) calibration. All measured results were acquired using 50Ω termination impedances. Fig 3 shows the two-port characterization configuration applied to all devices tested. Mean values for measured resonant frequency (f_o) and extracted motional capacitance (C_m) (which captures the transduction efficiency) for all devices across three samples are summarized in Table 1. It can be seen that the measured and simulated results for f_o and C_m agree well. Fig 4(a) compares the measured electrical transmission magnitude for R1 and R3 from one die sample. It can be seen that Q_u of R3 is about four times of R1, reducing insertion loss by 7dB. Fig 4(b) plots the values of Q_u for all 12 devices measured. It can be seen that the variation of Q_u is consistent across all three samples. R3 has the highest Q_u consistently, though all 3 variants with holes yield notably higher Q_u's (by at least 2.7 times) compared to R1. These results agree with the predictions from FE simulations.

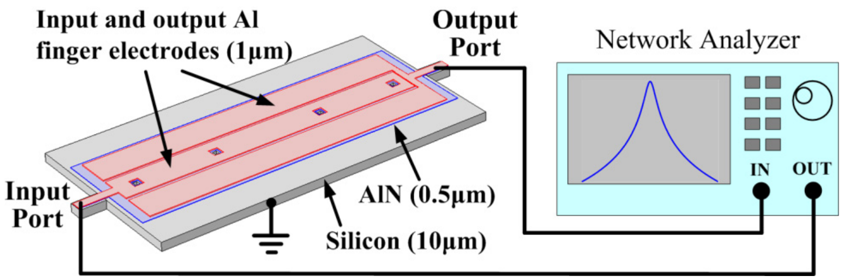
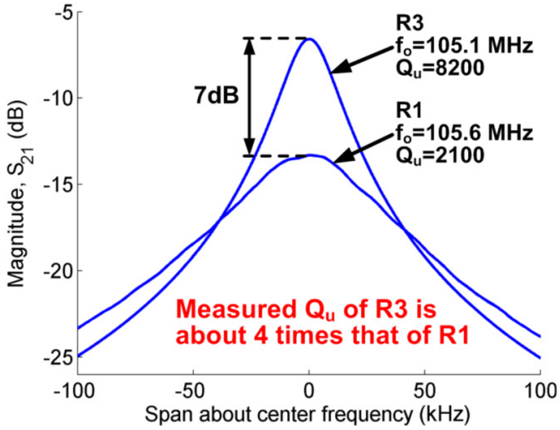


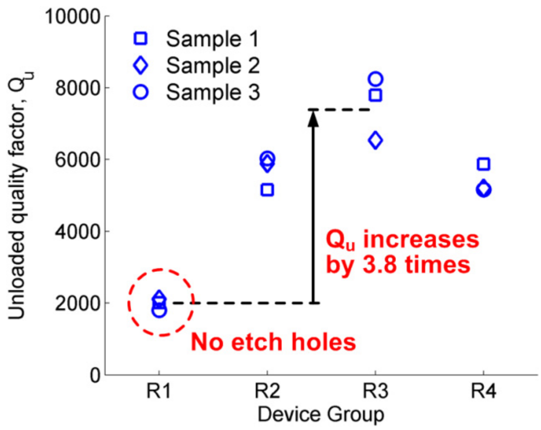
Fig. 3. Two-port electrical characterization configuration applied to all devices with the thicknesses of the various structural films labelled.

Table 1. Comparison of measured results (mean values from three samples) against FE simulations

		R1	*R2*	*R3*	*R4*
***S1, S2* (µm)**		NA	280, 32	320, 130	320, 160
FE Sim	***f_o (MHz)***	105.673	105.028	105.191	105.138
	C_m (fF)	2.04	1.60	1.72	1.49
Measured	***f_o (MHz)***	105.598	104.967	105.125	105.052
	C_m (fF)	2.09	1.36	1.62	1.46
	Q_u	2000	5700	7500	5400



(a)



(b)

Fig. 4. (a) Measured S_{21} electrical transmissions (magnitude) for R1 and R3 from one sample (Similar measured results observed on other two samples); (b) Comparison of unloaded quality factors (Q_u) among different device groups (R1~R4) measured across all three samples where the dotted lines correspond to the respective average values.

4. Conclusion

This work demonstrates that strategic placement of etch-holes in a 105MHz laterally-vibrating TPoS resonator can significantly boost its unloaded quality factor. The increase in unloaded quality factor resulting from adding holes is about 3.8 times on average for the design with the largest improvement in quality factor. FE simulation results suggest that the holes serve to suppress the movement on the supporting tethers and thus reduce anchor loss.

Acknowledgements

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