CROSS-SECTIONAL QUASI- LAMÉ MODES IN THIN-FILM PIEZOELECTRIC-ON-SILICON RESONATORS

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ABSTRACT

In this work, it is demonstrated for the first time that cross-sectional quasi-Lamé modes (CQLM) could be efficiently excited in silicon with reasonably high quality factor (*Q*). Third-harmonic Lamé modes of a silicon block are piezoelectrically exited in thin-film-piezoelectric on silicon (TPoS) resonators in which the thickness is chosen to be in proximity of half acoustic wavelength. Finite element analysis is used to show that the support loss in these resonators could be reduced by an order of magnitude through usage of acoustic isolation techniques. A quality factor of 14,500 is measured in partial vacuum for a third-harmonic 67 MHz CQLM-TPoS resonator designed within a circular acoustic isolation frame and fabricated on a 40μm thick silicon-on-insulator (SOI) substrate.

INTRODUCTION

Planar Lamé modes are commonly excited in capacitive silicon resonators at low-frequencies (MHz regime) and offer unique properties such as turn-over temperatures higher than any other conventional modes in degenerately doped silicon [1]. Such resonators are great candidates for extremely stable reference oscillators (e.g. oven controlled MEMS oscillators).

Planar Lamé modes, however, can't be efficiently excited in silicon through piezoelectric transduction. This is because the sputtered piezoelectric thin-films such as AlN are isotropic in the plane of the substrate. Therefore, the opposing in-plane stress components of a planar Lamé mode, result in near-zero charge accumulation on metal electrodes placed across the thin piezoelectric film (Fig.1).

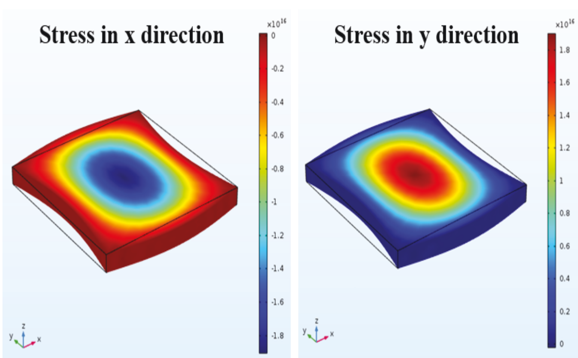

Figure 1: The simulated stress field in x and y direction for a planar Lamé mode. In each half vibration cycle, stress field is tensile in one direction and compressive in the other direction and because of that, such planar Lamé mode cannot be excited piezoelectrically.

On the other hand, Cross-sectional Lamé mode resonators (CLMR) have been recently demonstrated in thin-film AlN resonators [2,3] by targeting Lamé modes in the thickness of the AlN slab. These resonators offer coupling factors larger than what is achievable in lateral-extensional mode (contour-mode) resonators due to the fact that in CLMRs both d_{31} and d_{33} piezoelectric coefficients constructively contribute in the excitation of a two-dimensional mechanical vibration (excitation of the Lamé mode in the cross section of AlN film). Contrary to the case of FBAR resonators in which the center frequency could mainly be tuned by varying the thickness of the resonator, in CLMRs the center frequency could be defined lithographically (to some degree) due to the dependency of center frequency on both the thickness of the film and also to the lateral (in-plane) dimension. However, the achievable center frequency is limited to relatively high frequencies since the thickness of the sputtered AlN layer can't be practically more than a few micrometers. Also to guarantee the maximum coupling factor, the wave displacement in lateral and thickness directions should be almost equal.

In this work we first demonstrate that cross-sectional *quasi*-Lamé modes (CQLMs) could be efficiently excited in silicon with reasonably high *Q* using a thin-film piezoelectric transducer sputtered on top of the substrate. Next, we will propose an acoustic isolation technique to effectively reduce support loss for the CQLM resonators implemented in the thin-film piezoelectric-on-silicon (TPoS) platform. Finally, the frequency responses measured for CQLM-TPoS resonators fabricated on a relatively thick silicon-on-insulator (SOI) substrate (40μm) are presented in partial vacuum.

CQLM-TPOS RESONATORS

Overtone lateral-extensional (contour) resonance modes of a silicon block have been utilized in TPoS resonators to achieve a wide range of frequencies in the past [4,5]. In such resonators the d_{31} piezoelectric coefficient is mainly responsible for energy coupling between the mechanical and electrical domains as the z-axis electric field between the metal electrodes is transduced to in-plane xy stress and vice versa. The higher harmonics in such resonators are excited by forming an interdigitated electrode pattern on the rectangular resonator body (Fig. 2.a). The distance between two adjacent fingers is called the finger pitch (*FP*) and is equal to the half wavelength. *FP* is typically chosen larger than the thickness of the silicon block as a clean lateral-extensional mode shape is only achieved if the thickness to wavelength ratio is small. The simulated mode-shape of a 126μm × 50μm × 8μm (6μm silicon+2μm AlN) thin-film piezoelectric-on-silicon (TPoS) slab is presented in Fig. 2.b.

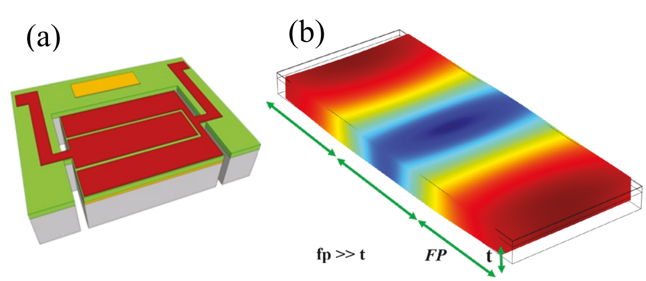

Figure 2: A schematic viewgraph of a two-port third-order TPoS resonator (a) and the Stress field for lateral-extensional mode TPoS resonator(b).

In the same rectangular block resonator, the in-plane extensional mode will deform and finally cease to exist as the thickness of the slab approaches the finger pitch. Instead, in such structures a different resonance mode evolves in which a mode-shape similar to that presented in Fig. 1 develops on the cross section of the slab; hence the name cross-sectional Lamé modes [2]. This mode can be exited using the thin piezoelectric film deposited on the slab, as the electrical charge corresponding to the opposite in-plane and out-of-plane stress components will constructively combine through opposite signs of d_{31} and d_{33} piezoelectric coefficients in AlN (Fig. 3.a). It should be noted that this mode deviates from pure Lamé-mode properties as the presence of the AlN and the metal layers disrupts the symmetry of the acoustic medium in the cross section of the resonator. Therefore, we will refer to such modes as Cross-Sectional Quasi Lamé modes (CQLM).

The electrode design for these resonators is the same as those used in lateral-extensional mode resonators (i.e. interdigitated pattern). The third-order harmonic CQLM in a 126 µm (3×42 µm) × 50 µm × 42 µm (40µm silicon+2µm AlN) thin-film piezoelectric-on-silicon (TPoS) slab is presented in (Fig. 3.b). The total displacement is shown in 3D to emphasize the close resemblance of this mode to a pure Lamé mode; hence the name *quasi*-Lamé.

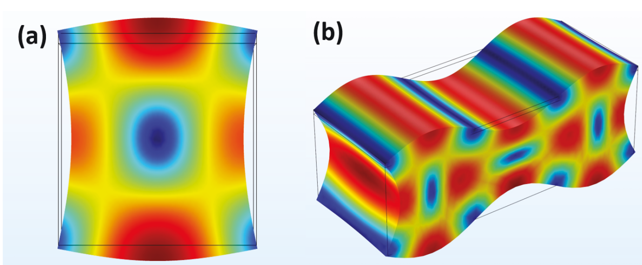

Figure 3:The simulated total displacement in a fundamental- (a) and third-harmonic (b) CQLM-TPoS resonator.

In this work, CQLM-TPoS resonators are fabricated with a finger pitch (35 µm or 51 µm) that differs from the thickness (42 µm). Nevertheless, the quasi-Lamé mode is detectable. The simulated mode shape for a third-harmonic CQLM in a 153 µm x 226 µm x 42 µm rectangular block is shown in Fig.4 highlighting the similarity of the mode to a pure Lamé.

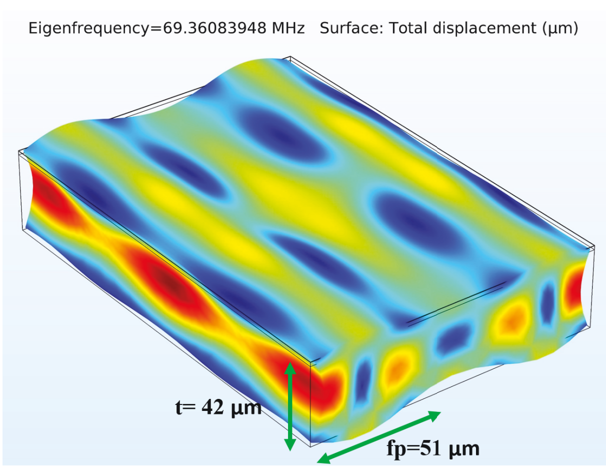

Figure 4: The simulated mode shape for a 153 µm×226 µm × 42 (40 µm of silicon + 2 µm AlN) block. The ~69 MHz simulated center frequency matches the 67 MHz measured center frequency fairly well.

SUPPORT LOSS IN CQLM-TPOS RESONATORS

Achieving reasonably high *Q* is crucial in most applications such as oscillators and sensors since resonator *Q* is directly impacting the system noise floor. For piezoelectric resonators, support loss, interface loss and electrical losses are the main sources of energy dissipation.

Common methods to avoid excessive support loss include: placing the tethers at pseudo-nodal points, optimizing tether geometry and dimensions, using planar acoustic reflector's, etc. For CQLM-TPoS resonators, there are no nodal points at the side of the resonator body. This is because, the Lamé mode is formed in the cross section of the resonator and therefore a large portion of the acoustic energy would be transferred to the substrate through tethers. Consequently, implementation of a planar acoustic reflector by etching trenches around the device [6,7] is an attractive solution. By placing these trenches at a proper distance, the reflected acoustic wave would constructively interfere with the standing waves inside the resonant body. In order to optimize the design of CQLM-TPoS resonator, a perfectly matched layer (PML)-based model is developed in COMSOL to predict the support *Q*. The PML region should be large enough to attenuate all the acoustic wave propagating through this medium.

In this work a novel circular frame around the resonator body is proposed to efficiently isolate the acoustic cavity from the substrate and to reduce the support loss. The COMSOL model used for simulating the support *Q* of a third-order CQLM-TPoS resonator enclosed within the acoustic isolation frame is shown in Fig. 5. A One-way symmetry is used in the model to reduce computational load.

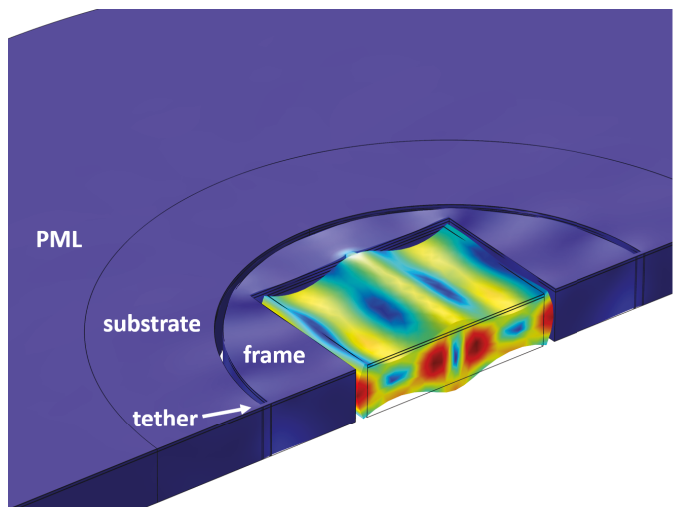

Figure 5: The PML-based finite element model developed for support loss prediction of a 153µm × 226µm × 42µm (silicon + AlN) device with isolation frame. There are no nodal points at the side of the resonator. For the resonators within an acoustic frame, the support loss is effectively reduced.

The dimension of the described acoustic isolation frame (i.e. the diameter) is varied to characterize the support *Q*. The simulated *Q* for the resonators with and without reflector frame confirm the substantial improvement that could be achieved with an isolation frame provided that the isolation frame is designed properly (Table.1). For the reflected wave to be constructively interfering with the resonator's standing wave, the acoustic isolation frame should have a diameter of (2n×λ/4) + 2 × (tether-length). The support quality factor is improved by an order of magnitude when the frame diameter is an even factor of the quarter acoustic wavelength. The optimum reflector distances are studied thoroughly in a recent work of our group [7].

Table 1: Modeled support quality factor for CQLM resonators with and without acoustic isolation frame

	Resonator without isolation frame	**Resonator with isolation frame**			
Isolation frame diameter	–	**2×*tl* + 3λ**	**2×*tl* + 3λ + λ/4**	**2×*tl* + 3λ + 2λ/4**	**2×*tl* + 3λ + 3λ/4**
***Q* (*k*)**	**4.5**	**40.1**	**3.4**	**61.2**	**7.6**

** In this table tl is the tether-length and λ is the acoustic wavelength.*

CQLM-TPOS RESONATORS FABRICATION

CQLM-TPoS resonators are fabricated on a relatively thick (40µm) degenerately n-type doped <100> SOI substrate in a five mask process. The sputtered AlN film is 2µm thick and is sandwiched between two 100nm thick layers of Molybdenum. First, the Mo/AlN/Mo stack would be sputtered and the top metal is dry-etched in an SF_6/O_2 plasma to shape the top electrodes (Fig. 6.a). Then, the AlN is wet etched in a heated TMAH solution to create access to the bottom electrode (Fig. 6.b). The resonator body is then shaped by plasma etching the full stack of material down to the SOI buried oxide (BOX) layer (Fig. 6.c). Handle layer silicon is then etched from the backside in a deep-reactive-ion-etching chamber using Bosch process and the resonator is finally released by wet etching the BOX layer in a buffered oxide etchant (BOE) (Fig. 6.d).

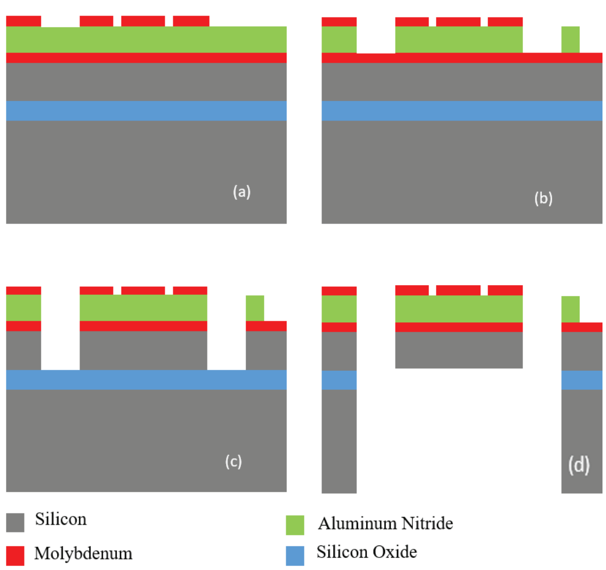

Figure 6: The simplified process flow for fabrication of the CQLM-TPoS resonators.

The scanning electron micrographs (SEMs) of two similar fabricated devices one directly connected to the substrate and the other surrounded with a circular acoustic isolation frame are shown in Fig.7 and Fig.8.

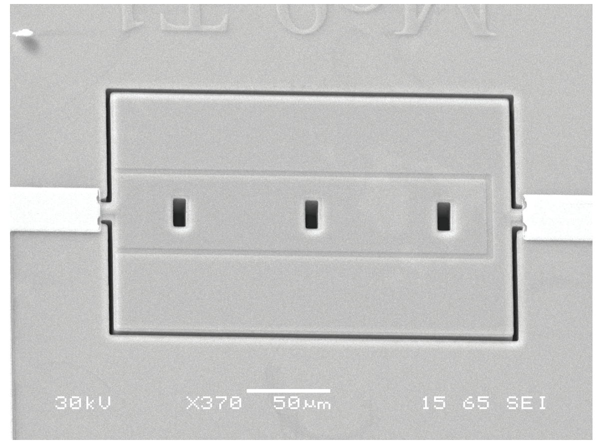

Figure 7: The scanning electron micrograph (SEM) of the third-order CQLM-TPoS resonators without acoustic isolation frame.

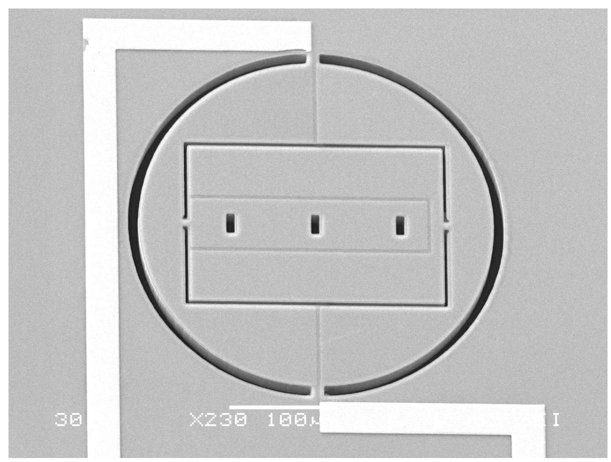

Figure 8: The scanning electron micrograph (SEM) of the third-order CQLM-TPoS resonators with acoustic isolation frame.

EXPERIMENTAL RESULTS

The frequency response of fabricated CQLM-TPoS resonators are measured both in atmospheric pressure and in partial vacuum. Third-order CQLM-TPoS resonators with a finger pitch (FP) of 51 µm and a seventh-order resonator with a finger pitch of 35µm are characterized using a Rohde & Schwarz *ZNB 8* network analyzer and a pair of GSG probes (Cascade Microtech Inc) at ambient temperature. The loaded quality factors (Q_{loaded}) are measured and the unloaded quality factors are extracted based on the results.

For the third harmonic CQLM, the quality factor is measured both with and without isolation frame in partial vacuum (Fig.9). The first order lateral-extensional mode of these resonators is also measured for comparison purposes. As seen, for the resonator with an acoustic isolation frame a significantly improved *Q* is measured (from 4.6k to 14.5k). By comparing the data in Table.1 and the measured quality factor for the resonator without isolation frame it could be concluded that the support loss is the dominant source of loss in the CQLM-TPoS resonators. This loss could be significantly improved by designing the CQLM-TPoS resonator within a properly designed acoustic isolation frame.

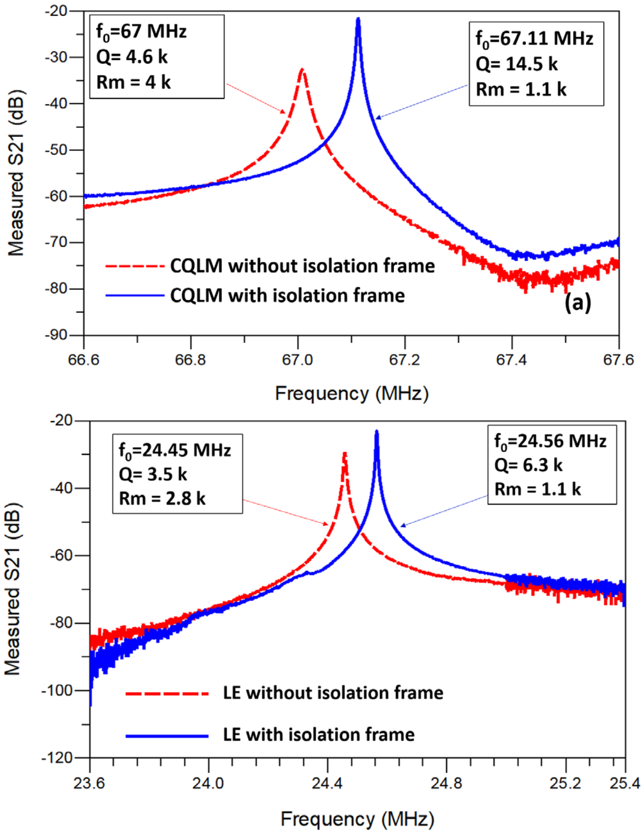

Figure 9: The measured S21 plots for a third-order CQLM (a) and first order lateral-extensional mode (b) in vacuum for resonator with and without reflector frame. Results support that the isolation frame efficiently reduces the support loss.

A seventh order CQLM is also measured for a TPoS resonator with a finger pitch of 35µm without an acoustic isolation frame and the frequency response is shown in Fig.10. A seen, the motional resistance has improved from ~4 kΩ for the third-harmonic without the frame to ~1 kΩ when the higher-order harmonic CQLM (seventh order) was excited.

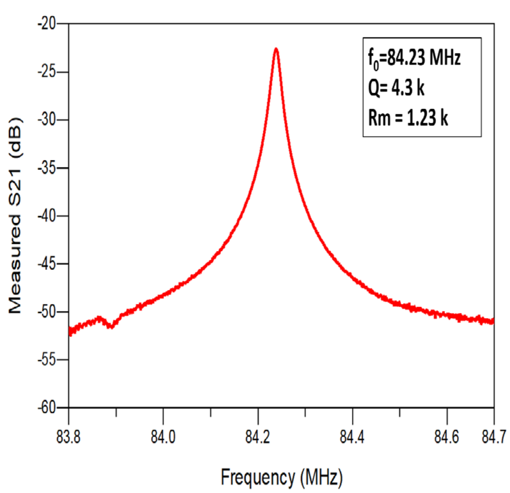

Figure 10: The measured frequency response for seventh order CQLM-TPoS resonator without an acoustic isolation frame.

CONCLUSION

In this paper, a new class of resonators coined as cross-sectional quasi Lamé mode (CQLM) thin-film piezoelectric-on-silicon (TPoS) is introduced for the first time. These resonators were fabricated on an SOI wafer and an acoustic isolation frame was used to effectively improve the support quality factor. Frequency response of these resonators are measured for the resonators with and without acoustic isolation frame. A 14500 quality factor was measured for a CQLM resonator with an isolation frame at ~67MHz. The presented CQLM-TPoS resonators are believed to be one of the best candidates for extremely stable time keeping applications.

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