SUBSTRATE-DECOUPLED SILICON DISK RESONATORS HAVING DEGENERATE GYROSCOPIC MODES WITH Q IN EXCESS OF 1-MILLION

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ABSTRACT

This paper details a center-supported solid disk resonator in <100> single-crystalline-silicon (SCS) that uses a novel substrate decoupling feature to achieve ultra-low dissipation gyroscopic modes with small frequency split. The secondary bulk acoustic wave (BAW) elliptic modes (m = 3) of a 2mm diameter substrate-decoupled disk resonator exhibit quality factor (*Q*) of ~1.3 M with 40 ppm frequency split (as fabricated) at 2.745 MHz. *Q*-factor remained in excess of 1 million at pressure levels as high as 500 mTorr. The measured temperature behavior of the *Q*, which is mostly limited by thermoelastic damping (TED), is in very close agreement with FEM predictions.

KEYWORDS

Bulk acoustic wave resonator, micromachined gyroscope, substrate decoupling, thermoelastic damping, high Q

INTRODUCTION

Bulk acoustic wave (BAW) disk resonators are of great interest in a wide range of applications [1-3]. In particular, axisymmetric disk resonators possess degenerate modes that can be utilized for high frequency mode-matched resonant gyroscopes [2]. Small form factor, large bandwidth and superior shock and vibration resistance make BAW gyroscopes ideal for use in many applications, including automotive, consumer electronics and personal navigation systems.

Mode-matched resonant gyroscopes are based on the Coriolis induced transfer of energy between two vibration modes of a microstructure (gyroscopic modes). Under mode-matched condition, the rotation-induced Coriolis signal is amplified by the quality factor (*Q*) of the sense mode. Due to *Q* amplification, gyroscopes operated in mode-matched configuration offer higher sensitivity and reduced Brownian noise.

To reduce the Brownian noise to tactical and navigational grade requirements while maintaining a small form factor, it is desirable to maximize *Q* of the degenerate modes of a disk BAW gyroscope to reach its intrinsic limits [4]. In this paper, a novel design strategy is introduced to substantially decouple the bulk acoustic modes of a solid disk from the underlying substrate to create a virtually levitated resonator [5], which exhibit very high *Q* gyroscopic modes limited by its intrinsic loss only.

ENGINEERING THE QUALITY FACTOR

Energy dissipation in a micromechanical resonator is a composition of different individual mechanisms that can be classified into intrinsic and extrinsic types [6]. Major extrinsic mechanisms are squeeze-film damping (SFD), surface and support loss, whereas main intrinsic mechanisms are thermoelastic damping (TED), and material quantum loss (the Akhiezer effect in the low to mid frequency resonators). The overall Q factor can be expressed as:

$$\frac{1}{Q} = \frac{1}{Q_{SFD}} + \frac{1}{Q_{Surface}} + \frac{1}{Q_{AKE}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{Support}} \quad (1)$$

Squeeze film damping, which is a consequence of the interaction between resonator and the surrounding gas, can be eliminated by operating the resonator in low pressure levels [7]. Surface loss that relates to scattering losses due to roughness in the device surface [8] is considered of minimal contribution because of relatively small surface-to-volume ratios in BAW resonators and polished surfaces. Therefore, for a BAW resonator operating in vacuum, the main limiting factors of *Q* are TED, Akheizer (AKE) and support loss. Support loss has a high design dependency and can become the dominant loss mechanism at any frequency due to design and fabrication imperfections. To practically bind the *Q* to intrinsic mechanisms and have a substrate-decoupled structure, support loss needs to be at least an order of magnitude smaller than TED and AKE, which requires novel engineering and design.

Support loss refers to the vibration energy of a resonator transmitted and dissipated through its support into the substrate. An upper bound for this lost energy can be calculated by integrating the elastic strain energy density (ESED), a product of stress and strain imparted by resonator into the substrate, throughout the volume of support region [5]. Qualitatively, the optimum location to anchor the structure is places with minimum displacement and low ESED levels. The concept of considering ESED to evaluate the proper anchoring position and analytically calculate the support loss has been previously utilized for simple structures with isotropic material properties [9]. However, finding closed-form expressions for TED and support loss in resonators with complex geometry implemented in anisotropic crystalline materials is a very difficult task, if not impossible; therefore, finite element modeling (FEM) is widely used to quantify those values.

This work focuses on secondary elliptic vibration modes (m = 3) of a center-supported disk for its lower ESED at the central area and potentially lower support loss compared to primary elliptic modes (m = 2), (figure 1a). <100> SCS is used as structural substrate because of its manufacturability advantages compared to <111> SCS. FEM studies of TED, SFD, and support loss by the use of perfectly-matched layers (PMLs) [10], are implemented in COMSOL-multiphysics.

Substrate-decoupled resonator design

It can be shown that a solid disk resonator exhibits very small TED for in-plane elliptic modes, but perforations introduced in SOI-based disk resonators for releasing purposes results in increased TED [6]. Therefore there is a motive to remove the perforations and release the devices through backside processing. Anisotropy of <100> SCS results in a large frequency split between primary elliptic degenerate modes of a solid disk (m = 2), making them inapplicable for gyroscope implementation. Although this anisotropy does not introduce a frequency split for secondary elliptic modes (m = 3), it couples the in-plane vibration energy to translational displacements of the central area toward antinodes of the mode. This translational movement exerts large shear stress at the support-substrate interface (Figure 1c) and results in a large support loss. FEM study predicts that for a 2 mm diameter center supported solid disk, despite Q_{TED} >10 M, $Q_{Support}$ is smaller than 30 k, significantly limiting the overall Q. Support loss for these gyroscopic modes can be minimized by blocking the acoustic energy path toward support along their plane of operation. This is realized by introducing axisymmetric decoupling features into the structure with 30 degrees offset for m = 3 degenerate modes (Figure 1b). Optimum geometry of decoupling features has been obtained through a series of FEM simulations of $Q_{Support}$ using PMLs. For a 1mm radii disk structure with support radii of 50 um, the inner radius (R_i) was fixed at 100 um to ensure enough room for defining support through wet release, then $Q_{Support}$ was simulated with outer radius (R_o) swept from 100 µm to 350 µm to find the optimum range of R_o, with minimum support loss found to be ~ 285 µm (Figure 1b, Step1:red curve). Similarly, to define the optimum range of R_i, R_o was fixed at the optimal value of 285 µm and R_i was swept to find the optimum R_i value of 100 µm (Figure 1b, Step2:blue curve). Optimum value for θ was obtained as 20 degrees. Optimized design is expected to be 'virtually levitated' and have negligible support loss ($Q_{Support}$>100 M). Therefore Q_{total} is expected to be limited by intrinsic mechanisms comprising TED and AKE. A comparison between the optimized design and anisotropic solid disk shows a significant reduction in displacement of central area, which is very close to the displacement of an isotropic structure, resulting in reduced shear stress that justifies the boost in $Q_{Support}$ (Figure 1c).

Although decoupling features are designed to diminish support loss, they result in increased TED. Series of FEM thermoelastic study showed an exponential drop of Q_{TED} with increased size of decoupling features. Converged thermoelastic damping FEM study estimates Q_{TED} ~ 1.8 M for m=3 degenerate modes at 2.77 MHz for the optimized design. Considering the quantum limit of SCS on *f-Q* product, Q_{AKE} is estimated smaller than 8 M for this range of

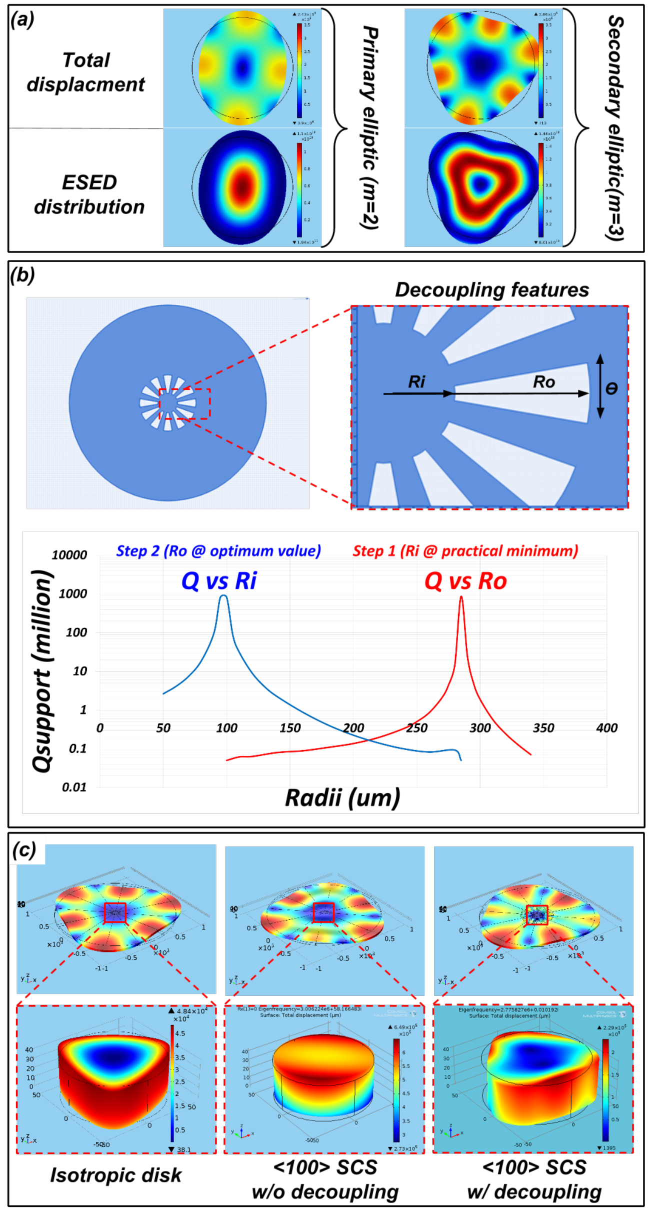

Figure 1: a) ESED distribution for primary (m = 2) and secondary (m = 3) elliptic modes of a disk resonator. b) Axisymmetric decoupling features and critical dimensions (R_i, R_o, θ) optimization. (Red curve): FEM simulated $Q_{Support}$ of a 1 mm radii disk structure with support radii of 50 µm, R_i of 100 µm, and Ro swept from 100um (solid structure) to 350 µm (location with nearly maximum ESED). $Q_{Support}$ peaks at R_o=285 µm as optimum value. (Blue curve): simulated $Q_{Support}$ of the disk structure with R_o of 285 µm, and R_i swept down from 285 µm (solid structure) to 50 µm (support periphery). $Q_{Support}$ peaks at R_i=100 µm as optimum value. c) Displacement of central area: (left) isotropic disk with minimum displacement, (middle) anistropic SCS Disk disk w/o decoupling showing large central displacement, (right) anisotropic SCS disk with optimized decoupling features showing minimized displacement at central area.

frequency. Therefore with major contribution from TED and AKE for a substrate decoupled structure, the overall Q of m=3 degenerate modes of the optimized design is estimated at ~1.48 M in vacuum (surface loss is perceived to be minimal for BAW resonators). Although introducing decoupling features into solid disk increases TED, it is worthy of mention that loading of AKE would mollify that to a great extent, where estimated $Q_{TED+AKE}$ for structure without and with decoupling are ~4 M and ~1.48 M respectively. Besides, the rewarding well-behaved Q-factors over a range of temperature due to ultra-low support loss validate the importance of substrate decoupling.

FABRICATION AND MEASUREMENT

Engineered solid disk resonators were fabricated using front and backside processing of silicon-on-insulator (SOI) substrate with 40 µm thick device layer. One of the advantages of implementing the disk resonators on SOI substrate is to use the buried oxide layer (BOX) for central post. To define the resonating disk structure and capacitive gaps, PECVD silicon dioxide layer was deposited as anisotropic etching mask and patterned through consecutive photolithography and RIE processes. High aspect ratio trenches (20:1) were etched in an ICP-RIE tool using the Bosch process to define the resonator structure and electrodes. To access the buried oxide layer (BOX), custom shape openings were defined in the backside and etched through the handle layer. The disk resonator is released by wet etching of BOX in HF, while the support oxide pedestal is centrally defined and self-aligned through an array of holes at the center of the disk (Figure 2).

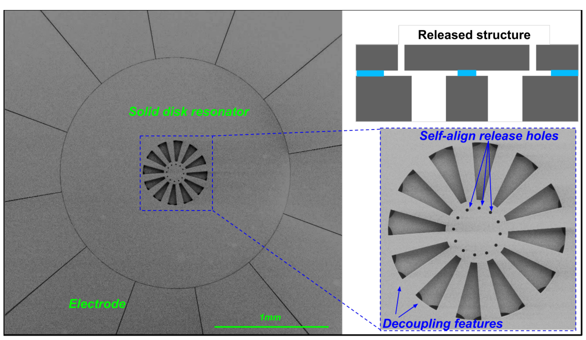

Figure 2: Substrate decoupled disk resonator fabricated on SOI substrate through front and backside DRIE processing and HF wet-release. The release holes around the center of the disk would define a centrally-located and self-aligned support pedestal.

Secondary elliptic degenerate modes (m = 3) of a 2 mm-diameter substrate-decoupled solid disk resonator were measured using a network analyzer to be at 2.745 MHz with frequency split less than 40 ppm and Q-factors of 1.23 M and 1.38 M, which are in close agreement to the estimated $Q_{TED+AKE}$. Other elliptical modes of the structure showed Q-factors of 0.414 M, 0.9 M and 1.44 M at 1.63 MHz, 2.27 MHz and 3.75 MHz respectively, also showing agreements with estimated $Q_{TED+AKE}$ (Figure 3). Figure 4 shows the measured temperature behavior of Q for m = 3 degenerate mode at elevated temperatures. The observed reduction in Q is attributed to elevated TED and is in close agreement with FEM simulation over 60 °C of temperature variation, which justifies TED as the dominant loss mechanism for the resonator, and verifies the effective decoupling of the resonant mode from the substrate.

Another advantage of high frequency BAW resonating structures is their high Q at higher-pressure levels compared to flexural mode devices. For the fabricated device, Q of m=3 mode remained greater than 1 M at pressure levels as high as 500 mTorr, which again is in close agreement with FEM study of SFD and TED (Figure 5).

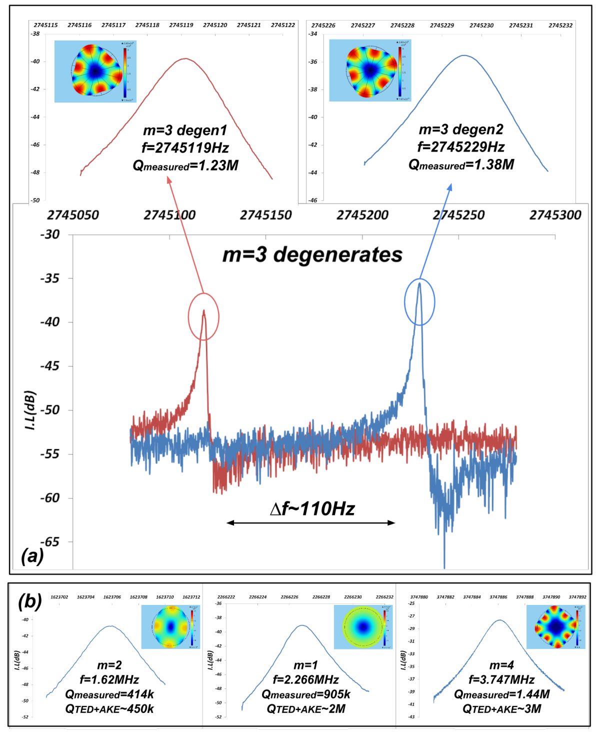

Figure 3: Measured Q-factor for multiple frequency signatures of structure including m=3 gyroscopic degenerate modes with less than 40 ppm frequency split, m=2, 4 and breathing mode (m=1)

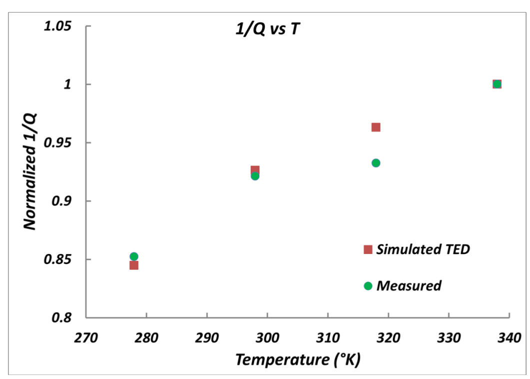

Figure 4: Measured and simulated values of normalized damping (1/Q) of m = 3 elliptic mode over temperature, showing close agreement.

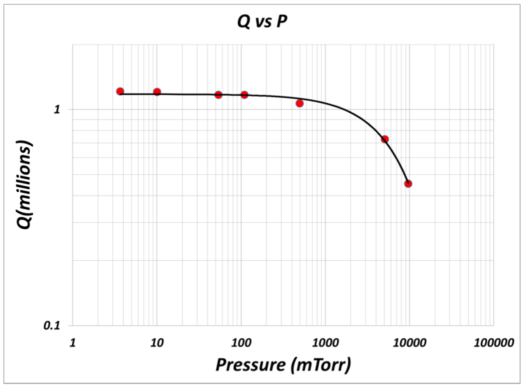

Figure 5: Measured Q and normalized simulated $Q_{TED+SFD}$ (exponential fit) for m = 3 mode at different pressures

CONCLUSIONS

A solid disk resonator pertains minimum TED for in-plane BAW elliptic modes, therefore it is desirable to eliminate perforations and fabricate the structures by front and backside processing of SOI substrates. Implementation of center supported structure on <100> SCS introduces large energy dissipation through support due to a large displacement of center resulted from anisotropy of the material. FEM study predicts a support limited *Q* for degenerate gyroscopic modes. To suppress the anticipated losses for m = 3 elliptic modes and improve the *Q* to be intrinsically limited, a novel substrate decoupled solid disk resonator is designed and fabricated. Degenerate gyroscopic modes with frequency split less than 40 ppm at 2.745 MHz were measured possessing Q-factors as high as 1.23 M and 1.38 M, which are in close agreement to simulated *Q*. Q-factor for m = 3 mode maintained its value in excess of 1M at pressures as high as 500 mTorr and followed the expected trend from FEM simulation over 60 °C of temperature variation. Although high frequency silicon resonators with Q-factors larger than 1 M have been shown before [11,12], our design is the first resonant structure possessing multiple ultra-high Q modes, including degenerate gyroscopic modes, with measured values very close to estimates obtained from COMSOL numerical simulations, paving the way for accurately engineering Q in microresonators. Solid state BAW resonators with such low energy dissipation have a great potential for improving the performance of mode-matched resonant gyroscopes, as well as oscillators and filters utilizing high Q elliptic modes, given the availability of low-cost vacuum packaging techniques.

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REFERENCES

[1] S. Pourkamali *et al.* “Low-impedance VHF and UHF capacitive silicon bulk acoustic wave resonators,” *IEEE Trans. Electron Devices*, vol. 54, pp. 2024-2030, 2007

[2] H. Johari *et al.* “Capacitive Bulk Acoustic Wave Silicon Disk Gyroscope” *Tech. Dig. IEEE Int. Electron Devices Meeting (IEDM 2006)*, San Francisco, CA, Dec.2006, pp. 513-516

[3] C. Nguyen, “MEMS technology for timing and frequency control” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol.54, pp251–70, 2007

[4] F. Ayazi, "Multi-DOF Inertial MEMS: From Gaming to Dead Reckoning," In *Proc. IEEE Transducers 2011*, Beijing, China, June 2011, pp. 2805-2808

[5] D. E. Serrano, “Integrated Inertial Measurement Units Using Silicon Bulk Acoustic Wave Gyroscopes”, *Ph.D. Thesis*, School of electrical and Computer Engineering, Georgia Institute of technology, October 2014

[6] F. Ayazi *et al.*, “ Energy dissipation in Micromecanical Resonators” In *Proc. SPIE 8031*, p.803119, 2011

[7] H. Sumali, “Squeeze Film Damping in the Free Molecular Regime: Model Validation and Measurement on a MEMS,” *Journal of Micromechanics and Microengineering*, vol. 1 , pp.2231-2240, 2007

[8] J. Yang *et al.,* “ Energy Dissipation in Submicrometer Thick Single-Crystal Silicon Cantilevers,” *Journal of Microelectromechanical Systems*, vol. 11, pp. 775-783, 2002

[9] Z. Hao *et al,*. “Support Loss in the Radial Bulk-mode Vibrations of Center-supported Micromechanical Disk Resonators,” *Sensors and Actuators A: Physical*, vol. 134, Issue 2, pp. 582-593 2007

[10] D. S. Bindel *et al.,* "Elastic PMLs for Resonator Anchor Loss Simulation," International Journal for Numerical Methods in Engineering, vol. 64, pp. 789-818, 2005

[11] J. E.Y. Lee *et al.,* “ 5.4-MHz single-crystal silicon wine glass mode disk resonator with quality factor of 2 million” *Sensors and Actuators A: Physical*, vol. 156, pp. 28–35, 2009

[12] L. Khine *et al.,* “High-Q bulk-mode SOI square resonators with straight-beam anchors” *Journal of Micromechanics and Microengineering*, vol. 19, p.015017, 2009

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