EXPERIMENTAL VALIDATION OF 3D INTUITIVE MODELING APPROACH FOR ANCHOR LOSS IN MEMS RESONATORS

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ABSTRACT

This work introduces a modified anchor loss model that is experimentally validated over an unprecedented range of low frequency (200 kHz – 13 MHz) devices. All measured designs, covering nearly two orders of magnitude in frequency, fell within 12% of the model's prediction. This experimentally validated model provides a framework for designers to modify designs (e.g., stem length, anchor area) in order to reduce anchor loss for arbitrary 3D geometries and identifies key process parameters (e.g., stress) for control of anchor losses.

INTRODUCTION

Silicon micro-electro-mechanical (MEMS) resonators have been developed for a variety of applications including mass sensing [1], energy harvesting [2], position navigating [3] and CPU clock timing [4-7]. In all of these applications, device performance is dependent on Quality factor (Q), which is determined by various energy dissipation mechanisms, such as air damping [8], Akhieser effect [9], Landau-Rumer effect [10], Thermoelastic dissipation (TED) [11], clamping loss [12-14], and surface loss [15]. While air damping, Akhieser, Landau-Rumer, and TED can be accurately modeled, clamping loss and surface loss models require further development. Energy dissipation can only be minimized with better understanding of fundamental energy dissipation mechanisms.

Accurate anchor loss models have been developed for a variety of 2D geometries and a select geometries in 3D, however, a general 3D model that is accurate for low to mid-range frequencies (Hz-kHz) has not been validated previously. One example geometry where analytical anchor loss models have been developed are in-plane flexural vibrations [12]. The technique of perfectly matched layers (PML) has been successful in predicting anchor loss behavior of high frequency resonators [13]. Our modeling approach captures the power loss through the anchor by directly calculating the stress and velocity fields at the anchor point. This approach has been successful previously [14] and this work applies this model to 3D wineglass mode resonators commonly utilized for MEMS gyroscopes.

Over the past two decades, high performance MEMS gyroscopes have been developed and successfully deployed in many military and commercial applications, including aeronautics and ballistics. While these MEMS gyroscopes have been very successful, the performance of these gyroscopes is still significantly inferior to the larger macroscopic gyroscopes. Many of these MEMS gyroscopes are operated at low frequencies and there is strong experimental evidence that suggests clamping loss is causing this performance degradation. Unfortunately, accurate clamping loss models applicable to these resonators have not been successfully utilized and research in this area to date has relied primarily on a trial-and-error approach.

This work outlines the development of a modeling approach that can accurately predict clamping loss in arbitrary 3D MEMS structures. This model also identifies key design characteristics that affect clamping loss and has the potential to lead the way in developing high performance MEMS gyroscopes.

The physical concept describing clamping loss is relatively simple. Clamping loss is caused by acoustic waves propagating in the substrate that carry energy away from the resonator. These waves are generated by the forces at the region of clamping, caused by the resonator's harmonic motion. Despite the relatively simple concept, clamping loss models in low frequency devices to date lacks sufficient experimental verification. Fabrication inconsistencies and fabrication induced stresses are likely causing the current conflicting experimental results. Our modified anchor loss model identifies intrinsic stress as a critical variable that provides a previously missing link enabling the accuracy of this approach.

METHOD

In order to model clamping loss, an intuitive modeling approach is adopted that involves calculating the stress and velocity fields at the anchor point and calculating the power loss per cycle. From the ratio of this power loss to the stored energy in the resonator, the quality factor can be calculated using the following equations:

$$Q_{Anchor} = \frac{\omega U}{\Pi} \quad \Pi = \iint_S \frac{1}{2} \text{Re} \left(-\sigma_{ij} v_j^* \right) \\ U = \frac{1}{2} \iiint_V \{ \sigma \}^T \{ \epsilon \}$$

Where Q_{Anchor} is the anchor limited quality factor, U is strain energy stored in the resonator, Π is the average power lost to the substrate, σ is stress, ϵ is strain and v is the velocity field at the anchor attachment point.

This approach is general and is directly related to a power calculation based on the force and velocity at the anchor point. The resonator dynamics are modeled utilizing a frequency response function, which is forced by a harmonic boundary load representing the actuation force (Figure 1). The high mesh density and accurate material parameters are crucial to obtaining accurate results with this approach. Intrinsic stress is included in the model as the calculated clamping loss and the resulting quality factor is highly dependent on this value. Q_{Anchor} can vary by orders of magnitude with changes in intrinsic stress, so knowledge of this parameter is critical to calculate accurate results.

For our resonators, a value of 0.3 MPa compressive stress was estimated from knowledge of the fabrication process. In order for the solution to converge, a damping term is included. The damping term is based on TED, the only other relevant damping mechanism in the experimental devices used in this work. TED is also modeled using the Consol multiphysics package.

In order to experimentally validate this model, ring resonators were fabricated using the Stanford vacuum Episeal process. The anchor structure design parallels the anchor structures of experimental gyroscopes, which often utilize a wine glass resonator mode attached to the substrate with a center post. Rings were scaled with various diameters in order to validate our modeling approach

Figure 1: A) Scaled wineglass ring resonators. B) Frequency response model utilizing a boundary load and quarter symmetry C) Mesh distribution. High density mesh required at anchor point. D) Power loss is modeled by calculating the stress and velocity distribution at the anchor point. E) SEM pictures of the top of a 226 μm ring and a cross-section of the same device.

across a wide frequency range (200 kHz – 13 MHz).

The stable manufacturing process provided by the Stanford *epi-seal* encapsulation [16] allows for thorough investigation of the various dissipation mechanisms since it provides consistency across hundreds of devices in a stable vacuum-sealed package. The *epi-seal* encapsulation process was proposed by researchers at the Robert Bosch Research and Technology Center in Palo Alto and then demonstrated in a close collaboration with Stanford University. This collaboration is continuing to develop improvements and extensions to this process for many applications, while the baseline process has been brought into commercial production by SiTime Inc.

RESULTS

Devices were tested using the HP 4920A Network analyzer and probed using a SUSS PM5 probe station, as seen in Figure 2. Several device designs, with radii 64 μm , 115 μm , 215 μm , 315 μm and 415 μm , were characterized and compared with simulated values.

Figure 2: Measurement setup for resonator characterization.

In order to compare experimental results to modeling, it is first necessary to identify the exact dissipation mechanisms for these ring resonators. Air damping was avoided with the vacuum encapsulation of the Stanford *epi-seal* process. Additionally, surface losses were likely negligible since the device dimensions provide a relatively low surface area to volume ratio compared to the nanoscale resonators where surface dissipation has been reported [17]. Also, at these lower frequency ranges, (200 kHz - 13 MHz) Akhieser, and Landau-Rumer are negligible. Therefore, TED and clamping loss were the only two relevant dissipation mechanisms for these resonators.

As can be seen in Figure 3 and Table 1, the measured Q was within 12% (approximately the experimental error) for each of the five different resonator designs spanning nearly two orders of magnitude in frequency. Our model combines the two relevant dissipation mechanisms, TED and clamping loss. These results represent unprecedented matching of experiment and anchor loss simulations for a broad range of low frequency resonators.

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Figure 3: Plot of measured and simulated values of different dissipation mechanisms. Each data point represents 5 devices. Q_{TED} was solved using COMSOL thermal mechanical multiphysics package. The simulated Q is within 12% of the measured Q for all resonators.

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Table 1: Measurement and simulation data

Frequency (Hz)	$Q_{MEASURED}$	$Q_{ANCHOR+TED}$ SIMULATED	Stress (MPa)
212,221	33148	39653	0.3
376,115	25070	25163	0.3
759,482	14659	12658	0.3
3,328,706	7517	8598	0.3
13,381,370	14246	13947	0.3

CONCLUSIONS

This work provides experimental validation of anchor loss models for an extensive range of low frequency (200 kHz – 13 MHz) devices. All measured designs, covering nearly two orders of magnitude in frequency, fell within 12% of the model's prediction. This experimentally validated model provides a framework for designers to modify designs (e.g., stem length anchor design) in order to reduce anchor loss for arbitrary 3D geometries and identifies key process parameters (e.g., stress) for control of anchor losses. Continued improvement in the understanding of energy dissipation will greatly improve the design of high quality factor resonators for the design of high performance MEMS gyroscopes.

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REFERENCES

- [1] Y. T. Yang, C. Callegari, X. L. Feng, K. L. Ekinici and M. L. Roukes, "Zeptogram-scale nanomechanical mass sensing," Nano Letters 6, 4, (2006).
- [2] S. P. Beeby, M. J. Tudor and N. M. White, "Energy harvesting vibration sources for Microsystems applications," Measurement Science and Technology, 17, 12, (2006).
- [3] E. P. Quévy and R. T. Howe, "Redundant MEMS Resonators for Precise Reference Oscillators," Technical Digest of the 2005 Radio Frequency Integrated Circuits (RFIC) Symposium., IEEE, Long Beach, CA 6/12-14/05,(2005), pp. 113-116.
- [4] R. Melamud, S. A. Chandorkar, S. F. Lord and T. W. Kenny, "Real-Time Temperature Compensation of MEMS Oscillators Using an Integrated Micro-Oven and a Phase-Locked Loop," Journal of Microelectromechanical Systems, 19, 1, (2010).
- [5] C. T.-C. Nguyen, "MEMS technology for timing and frequency control," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 54, 2, (2007).
- [6] K. Sundaresan, G. Ho, S. Pourkamali and F. Ayazi, "Electronically Temperature Compensated Silicon Bulk Acoustic Resonator Reference Oscillators," IEEE Journal of Solid-State Circuits, 42, 6, (2007).
- [7] D. Weinstein and S. Bhawe, "The Resonant Body Transistor," Nano letters, 10, 4, (2010).
- [8] M. Bao and H. Yang, "Squeeze film air damping in MEMS," Sensors and Actuators, 136, 1, (2007).
- [9] S. Chandorkar, M. Agarwal, R. Melamud, R. Candler, K. Goodson, and T. Kenny, "Limits of Quality Factor in Bulk-Mode Micromechanical Resonators,"

- International Conference on Micro Electro Mechanical Systems (MEMS), Tucson, AZ, 1/13-17/08, IEEE, 2008, pp. 13-17.
- [10] J. Hasson and A. Many, "Observation of Akhiezer and Landau-Rumer Regimes in the Frequency Dependence of Shear-Wave Lattice attenuation in CdS," *Physical Review Letters*, 35, 12, (1975).
 - [11] C. Zener, "Internal friction in solids: I. Theory of internal friction in reeds," *Physical Review*, 52, (1937).
 - [12] Z. Hao, A. Erbil, and F. Ayazi, "An analytical model for support loss in micromechanical beam resonators with in-plane flexural vibrations" *Sensors and Actuators A: Physical*, 109, 1-2, (2003).
 - [13] D. Bindel, E. Quévy, T. Koyama, S. Govindjee, J. W. Demmel, and R. T. Howe, "Elastic PMLs for resonator anchor loss simulation," *International Journal Numerical Methods in Engineering*, 64, 6, (2005).
 - [14] J. Judge D. M. Photiadis, J. F. Vignola, B. H. Houston, and J. Jarzynski, "Attachment loss of micromechanical and nanomechanical resonators in the limits of thick and thin support structures," *Journal of Applied Physics*, 101, (2007).
 - [15] Y. Wang, J. A. Henry, A. T. Zehender, and M. A. Hines, "Surface Chemical Control of Mechanical Energy Losses in Micromachined Silicon Structures," *Journal of Physical Chemistry B*, 107, (2003).
 - [16] R.N. Candler, et al. "Long-Term and Accelerated Life Testing of a Novel Single-Wafer Vacuum Encapsulation for MEMS Resonators." *Journal of Microelectromechanical Systems*, 15, 6, (2000).
 - [17] J. A. Henry, Y. Wang, D. Sengupta and M. A. Hines. "Understanding the Effects of Surface Chemistry on Q: Mechanical Energy Dissipation in Alkyl-Terminated (C₁-C₁₈) Micromechanical Silicon Resonators," *Journal of Physical Chemistry B*, 111, (2007).