Quality Factor Extraction and Enhancement Across Temperature in Ring Resonators

Anne L. Alter, Dustin D. Gerrard, Hyun-Keun Kwon, Gabrielle D. Vukasin, and Thomas W. Kenny, *Senior Member, IEEE*

***Abstract*— This work demonstrates that thin slots strategically placed in MEMS ring resonators are able to enhance the quality factor (Q) of the device operated in a wineglass mode in the isothermal region. The devices are optimized using COMSOL for an increased Q through increased slot size, using the Zener curve as a comparative baseline. These parts are fabricated and encapsulated in an ultra-clean environment, and tested in various temperature and pressure conditions to directly measure changes in anchor, gas, and thermoelastic dissipation across temperature. [2020-0156]**

***Index Terms*— Microelectromechanical systems, energy dissipation, thermoelastic dissipation, anchor damping.**

I. Introduction

THERMOELASTIC dissipation (TED) is a common damping mechanism in microelectromechanical (MEM) resonators. Zener first quantified this phenomenon in rectangular beam structures and formulated the upper limit of the quality factor (Q) derived from the relationship between the coupling of mechanical and thermal modes [1], [2]. Subsequent work built on this theory by studying the impact that slots in rectangular beams have on Q_{TED} [3], [4]. Slots impede heat flow across temperature gradients that form during beam bending and thus decrease energy dissipation and increase Q_{TED}.

Preliminary work has been done by Wong et. al. on another TED-limited device: ring resonators [5]. Hossain *et. al*. further quantified the effects of leg widths and leg geometries on TED in these ring resonators [6]; a preliminary study on the effects of adding slots to the rings was also included but focused on the adiabatic regime of the ring resonators and found a decrease in Q in this region [6].

Manuscript received May 12, 2020; revised June 13, 2020; accepted June 15, 2020. Date of publication July 10, 2020; date of current version October 7, 2020. This work was supported in part by the Defense Advanced Research Projects Agency (DARPA) grant "Precise Robust Inertial Guidance for Munitions (PRIGM)", managed by Dr. Ron Polcawich, under Grant N66001-16-1-4023, and in part by the National Science Foundation, at the Stanford Nanofabrication Facility (SNF), under Grant ECS-9731293. Subject Editor M. Rais-Zadeh. *(Corresponding author: Anne L. Alter.)*

Anne L. Alter, Hyun-Keun Kwon, Gabrielle D. Vukasin, and Thomas W. Kenny are with the Department of Mechanical Engineering, Stanford University, Stanford, CA 94305 USA (e-mail: annealtr@stanford.edu; ryankwon@stanford.edu; gvukasin@stanford.edu; kenny@cdr.stanford.edu).

Dustin D. Gerrard is with Invensense Inc., San Jose, CA 95110 USA (e-mail: dustingerrard@gmail.com).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JMEMS.2020.3004748

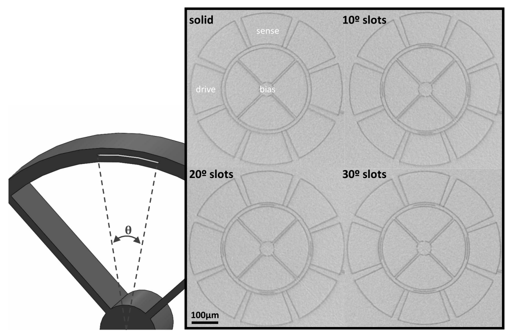


Fig. 1. Schematic of ring device showing slot parameter measured from the center point of the anchor; inset shows an x-ray image of fabricated devices, this is an internal layer in the encapsulated die with visible device layer and electrodes.

This work builds on previous studies by investigating the effect of slots in ring resonators operating in an isothermal region. We also include a comprehensive study of the effects of slot and diameter parameterization and quantify changes to all dissipation mechanisms. The ring resonators are centrally-anchored with four spokes that attach to a ring operating in the wineglass mode (Fig. 1 and 2). Slots are placed symmetrically in the four locations of greatest displacement (Fig. 1), where the largest temperature gradients occur.

II. Simulation

A finite element model (FEM) was used to model how the Q_{TED} in the wineglass mode changes with the addition of slots. The temperature fields for a set of 300μm diameter devices are shown in Fig. 2 and emphasize the temperature change at the regions of largest displacement. Overall, 12 designs of varying diameter (200μm through 400μm) and slot size (solid to 30° slots, see Fig. 1 for slot parameter definition) are fabricated and their Q is measured through a ringdown response in various temperature and pressure conditions.

The Q_{TED} was simulated across a range of frequencies and compared with Zener theory for beam resonators [1], [2], a modified Zener theory for disk resonator gyroscopes (DRGs) [7], and with actual fabricated parts (Fig. 3). It should be noted in Fig. 3 that the simulations account only for Q_{TED}, while the experimental points are

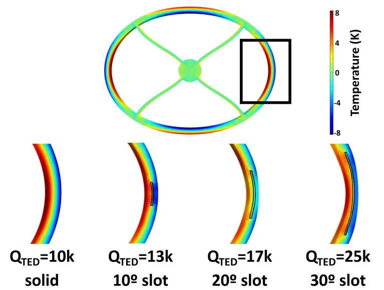


Fig. 2. TED finite element model simulations of wineglass mode in 300μm diameter ring showing temperature gradients forming in regions of greatest displacement.

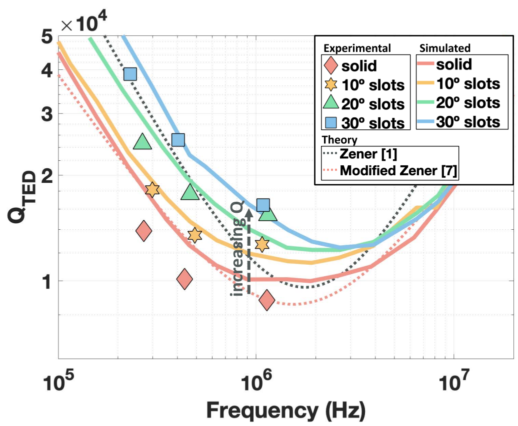


Fig. 3. Experimental measurements of Q_{TOTAL}; FEM simulation of Q_{TED} (solid lines) using parameters from [8]; compared with Zener theory for rect. beams [1] and modified Zener theory for ring resonators [7] (dotted lines).

measures of Q_{TOTAL}, as the vacuum encapsulated resonators could have small contributions from other sources, such as gas and anchor damping. Therefore, the simulated values represent an upper limit on the Q, which closely aligns with most of the experimental points (a few are higher than simulation due to experimental error). The Q of the fabricated slotted designs show up to a 4.5x Q enhancement depending on the diameter and slot condition chosen.

In order to quantify changes to other dissipation mechanisms, a focused ion beam (FIB) is used to open the encapsulation cavity of the devices in order to measure Q_{TOTAL} across pressure to extract Q_{GAS}. Devices opened via FIB were then pumped down to ultra-high vacuum and swept across temperature to a region where the coefficient of thermal expansion (CTE) of silicon is zero to analyze the quality factor dependence on temperature and measure Q_{ANCHOR}, given that thermal and pressure effects were eliminated.

III. Results

As shown in Fig. 4, the devices opened via FIB were swept across pressure and when compared with the pre-FIB Q, reveal the encapsulation pressure. We fit these results to squeeze-film

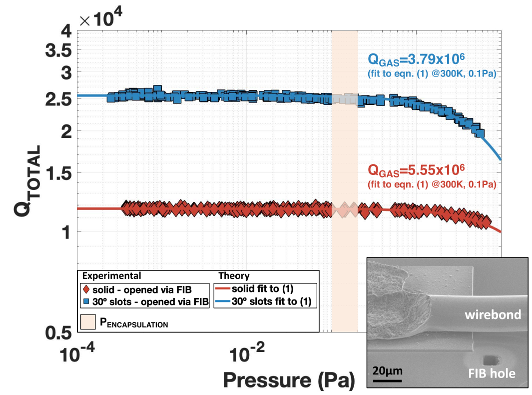


Fig. 4. Experimental measurements of $Q_{TOTAL}(P)$ at T = 300K (points); solid lines fit to (1) and Q_{GAS} (squeeze film damping) term extracted; FIB was used to etch the hole in the device encapsulation layer (shown in SEM inset).

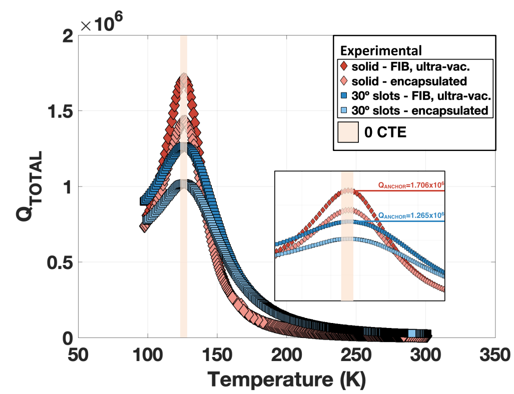


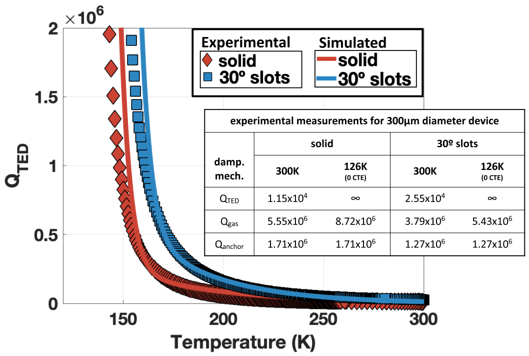
Fig. 5. Experimental measurements of $Q_{TOTAL}(T)$ in devices at ultra-vacuum (elimating the effects of Q_{GAS}) and encapsulated pressure (P$\sim$0.1 Pa); Q_{ANCHOR} was measured where CTE=0.

damping theory (1) in Fig. 4, where C is a constant, k_B is the Boltzmann constant, P is pressure, and T is temperature. We can see that the slotted devices actually have slightly more gas damping than the solid devices (3.79e6 vs. 5.55e6). This can likely be explained by an increased amount of squeeze-film damping within the actual slots.

$$Q_{TOTAL}^{-1} = Q_{LowP}^{-1} + Q_{gas}^{-1} = Q_{LowP}^{-1} + \frac{P}{C\sqrt{k_B T}} \quad (1)$$

In Fig. 5, we measure the Q across temperature at ultra-low pressures to extract the anchor damping [9]. The slotted devices, interestingly, increase the anchor damping (decrease Q_{ANCHOR}), which in itself warrants more study.

In Fig. 6 we simulate Q_{TED} across temperature and compare with experimentally extracted Q_{TED} values. To extract the Q_{TED} across temperature, we subtract it from the inverse sum of the measured Q_{TOTAL} ($\frac{1}{Q_{TOTAL}} = \frac{1}{Q_{TED}} + \frac{1}{Q_{GAS}} + \frac{1}{Q_{ANCHOR}}$). Q_{TOTAL} was measured in the temperature sweep



experimental measurements for 300µm diameter device				
damp. mech.	solid		30º slots	
	300K	126K (0 CTE)	300K	126K (0 CTE)
Q_{TED}	1.15×10^4	∞	2.55×10^4	∞
Q_{gas}	5.55×10^6	8.72×10^6	3.79×10^6	5.43×10^6
Q_{anchor}	1.71×10^6	1.71×10^6	1.27×10^6	1.27×10^6

Fig. 6. Experimentally measured Q_{TED} (points) compared with FEM simulated Q_{TED} (lines); close match with simulation suggests all dissipation mechanisms were measured.

(Fig. 5), Q_{ANCHOR} is assumed to be constant across temperature, and Q_{GAS} was fit to squeeze film damping theory with $\sqrt{T}$ dependence on temperature. The experimentally extracted Q_{TED} values closely match the finite element simulation, which validates all dissipation mechanisms were captured.

IV. Conclusion

Using strategically placed thin slots, we have enhanced the quality factor up to 4.5x in ring resonators. Furthermore, we present an experimental technique to extract the Q_{TED} of a resonator across temperature. We have observed that despite decreasing the TED by disrupting heat flow pathways, we slightly increase the amount of gas and anchor damping in these devices. These results have implications for MEMS designers trying to optimize device performance and sensitivity.

Acknowledgment

Special thanks to all the staff at SNF for their help during the fabrication process.

References

[1] C. Zener, "Internal friction in solids. I. Theory of internal friction in reeds," *Phys. Rev.*, vol. 52, no. 3, pp. 230–235, Aug. 1937.

[2] C. Zener, "Internal friction in solids II. General theory of thermoelastic internal friction," *Phys. Rev.*, vol. 53, no. 1, pp. 90–99, Jan. 1938.

[3] R. N. Candler *et al.*, "Impact of geometry on thermoelastic dissipation in micromechanical resonant beams," *J. Microelectromech. Syst.*, vol. 15, no. 4, pp. 927–934, Aug. 2006.

[4] D. D. Gerrard *et al.*, "Topology optimization for reduction of thermoelastic dissipation in MEMS resonators," in *Proc. 19th Int. Conf. Solid-State Sensors, Actuat. Microsyst. (TRANSDUCERS)*, Jun. 2017, pp. 794–797.

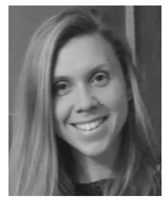
[5] S. J. Wong, C. H. J. Fox, S. McWilliam, C. P. Fell, and R. Eley, "A preliminary investigation of thermo-elastic damping in silicon rings," *J. Micromech. Microeng.*, vol. 14, no. 9, pp. S108–S113, Sep. 2004.

[6] S. T. Hossain, S. McWilliam, and A. A. Popov, "An investigation on thermoelastic damping of high-Q ring resonators," *Int. J. Mech. Sci.*, vol. 106, pp. 209–219, Feb. 2016.

[7] D. D. Gerrard *et al.*, "Manipulation of heat flux paths in thermoelastically damped resonators for Q optimization," in *Proc. IEEE 30th Int. Conf. Micro Electro Mech. Syst. (MEMS)*, Jan. 2017, pp. 1130–1133.

[8] S. A. Chandorkar *et al.*, "Multimode thermoelastic dissipation," *J. Appl. Phys.*, vol. 105, no. 4, 2009, Art. no. 043505.

[9] J. Rodriguez *et al.*, "Direct detection of akhiezer damping in a silicon MEMS resonator," *Sci. Rep.*, vol. 9, no. 1, pp. 1–10, Dec. 2019.

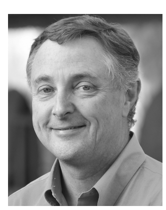


Anne L. Alter received the B.S. degree *(summa cum laude)* in mechanical engineering from Iowa State University in 2013 and the M.S. degree in mechanical engineering from Stanford University in 2017, where she is currently pursuing the Ph.D. degree. Her research interests include fatigue, nonlinear dissipation, and shape parameterization for TED manipulation.

Dustin D. Gerrard received the bachelor's degrees in mechanical engineering and mathematics from Brigham Young University and the M.S. and Ph.D. degrees in mechanical engineering from Stanford University. He currently works at the Research and Development, TDK-Invensense. His research interests are in computational methods for optimization of MEMS performance.

Hyun-Keun Kwon received the B.S. degree in electrical engineering from Korea University, Seoul, South Korea in 2013 and the M.S. degree in electrical engineering from Stanford University in 2016, where he is currently pursuing the Ph.D. degree in mechanical engineering. His research interests include fabrication and MEMS resonator ovenization.

Gabrielle D. Vukasin received the B.A. degree in astrophysics and mathematics from the Williams College in 2014 and the M.S. degree in mechanical engineering from Tufts University in 2016. She is currently pursuing the Ph.D. degree in mechanical engineering with Stanford University. Her research interests include the design and fabrication of MEM resonators with a focus on the characterization of energy loss mechanisms using wide-range temperature measurements of the quality factor of different resonators.



Thomas W. Kenny (Senior Member, IEEE) received the B.S. degree in physics from the University of Minnesota in 1983 and the M.S. and Ph.D. degrees in physics from the University of California at Berkeley in 1987 and 1989, respectively. He is currently the Richard Weiland Professor of mechanical engineering with Stanford University, where he directs research in a variety of areas, including resonators, wafer-scale packaging, cantilever beam force sensors, and novel fabrication techniques for MEMS.