EFFECT OF SUBSTRATE THICKNESS ON ANCHOR DAMPING IN MEMS DEVICES

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ABSTRACT

We present unexpected results showing that thinning the bottom substrate of a resonant MEMS tuning fork resonator decreases anchor damping. We also present findings that the tuning fork experiences more anchor damping when mounting the die with silver paste. This is important for wearable devices where minimizing the volumetric footprint of sensors is paramount.

KEYWORDS

Resonant MEMS, anchor damping, wearable devices, quality factor.

INTRODUCTION

MEMS are used as accelerometers, gyroscopes, timing references, etc. for many applications [1]. One increasingly popular application is wearable devices because MEMS have the advantage of smaller footprints and volumes than their macro-sized alternatives [2]. Size is important to wearable devices because their aim is to monitor data metrics of a person while being as minimally invasive and unencumbering to the wearer as possible. This means being as small, light-weight, and least power consuming as possible.

One way to adapt a MEMS device for use in wearable technology is to decrease the volume of the device. How does this affect the performance of the device? We study the quality factor of MEMS resonators in order to determine the effect of decreasing the volume on device performance. The quality factor is inversely proportional to the total damping of the resonator. The reciprocal sum of the quality factor due to each damping mechanism is the total quality factor, Q:

$$\frac{1}{Q} = \sum \frac{1}{Q_{factors}} = \frac{1}{Q_{Gas}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{Anchor}} + \frac{1}{Q_{Akhiezer}} + \frac{1}{Q_{Others}} \quad (1)$$

This builds on previous work in the community on measuring sources of damping in MEMS resonators [3-5]. Measurements of the quality factor over the temperature range of 80K to 300K are compared with temperature profiles of thermoelastic dissipation (TED), air damping and Akhiezer damping [6]. The double-ended tuning fork (DETF), operated in the mode in Figure 1c, is a device that has two clamped-clamped beams. The expected Q_{TED} is calculated [7]

$$Q_{TED} = \frac{\rho c_p}{E\alpha^2 T_o} \frac{1+(\omega\tau_n)^2}{\omega\tau_n} \quad (2)$$

where E is the Young's modulus, α is the coefficient of thermal expansion (CTE), T_o is the average temperature, ω is the resonant frequency of the beams, and τ_n is the thermal time constant.

Using this knowledge of Q_{TED} and ruling out other damping mechanisms, we can measure anchor damping.

EXPERIMENTAL METHOD

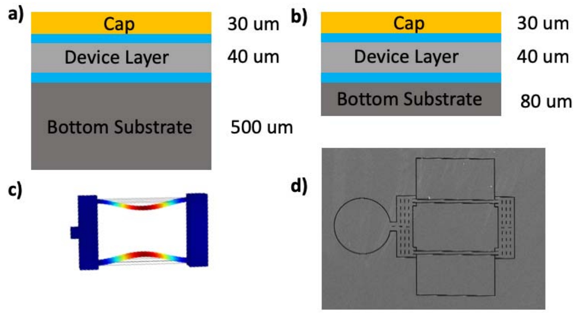

Figure. 1: a) Cross-section of thick die, b) cross-section of thin die, with oxide layers in blue (3 um thick), c) flexural mode of double-ended tuningfork, d) SEM of DETF.

These devices are sealed using a wafer-scale encapsulation process (0.1 to 1 Torr) [8]. The DETFs are tested in a pressure chamber that allows flowing liquid nitrogen to cool an individual die down to 80K. To measure Q, ringdown measurements of the DETFs are taken as they warmup to 300K over 4-5 hours. We measured Q(T) for DETFs anchored to thin and thick (Figures 1a,b) bottom substrates. After fabrication, part of the wafer was thinned by 420um using a DISCO backgrinder.

When performing these experiments, the dies are either silver pasted to the chip carrier, "pasted," or suspended on four wirebonds used to operate the DETF electrostatically, "floating," as seen in Figure 2. Previous studies have shown that pasting the die increases anchor damping [3].

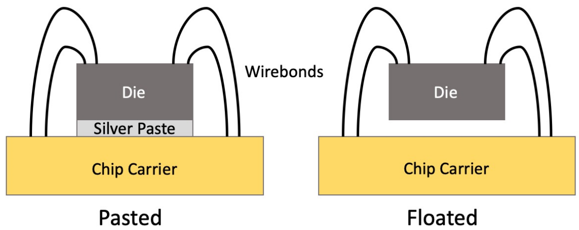

Figure 2: Cartoons of pasted and floated dies with wirebonds on a gold chip carrier.

BACKGROUND KNOWLEDGE OF Q(T)

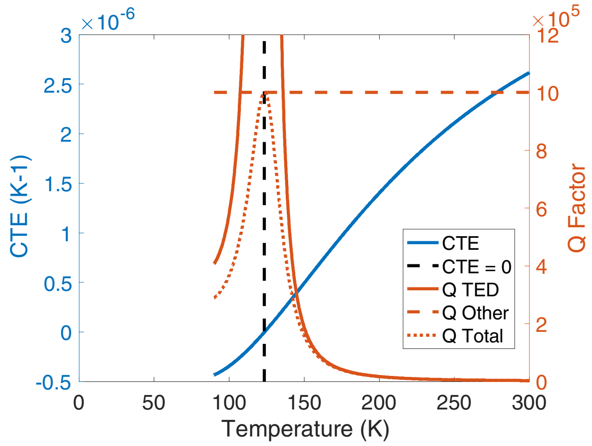

Figure 3: Coefficient of thermal expansion (CTE) of single crystal silicon [9]. Black dotted line denotes first zero-crossing of CTE. At the zero crossing, Q_{TED} comes to a peak at infinity (solid red). When there are other damping mechanisms present, Q_{Other}, the total Q looks like Q Total (fine dotted red).

The CTE has a temperature dependence (blue line in Figure 3) and a unique property of crossing zero at ~120K. When the CTE is zero, Q_{TED} goes to infinity. Thus, the experimentally measured Q at 120K is determined by the remaining damping mechanisms (Q_{Other}). This produces Q(T) plots where a peak occurs at the CTE zero crossing (fine dotted red line).

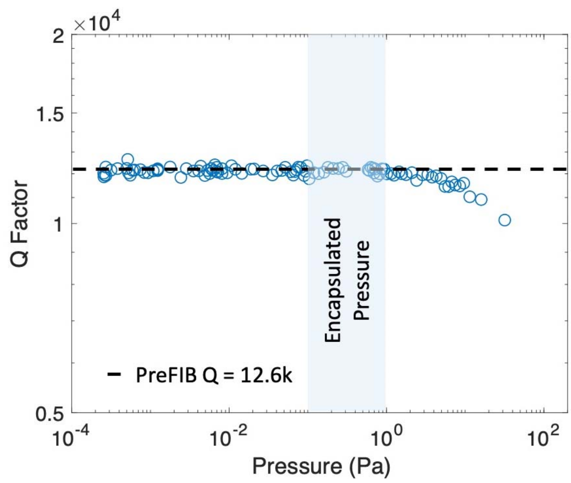

Figure 4: Pressure sweep, Q(P), of a DETF on a thick substrate. Dotted line represents quality factor at room temperature before venting the device.

The quality factor at the peak of Q(T) is the total quality factor due to the next limiting damping mechanism at the peak. Gas damping is eliminated as the next limiting mechanism by analyzing the pressure sweep, Q(P), performed on a vented part, which shows that the encapsulated Q, 12.6k, is the same as at ultra-high vacuum (Figure 4). Akhiezer loss is not a limiting factor because the f*Q product is not near the Akhiezer limit of silicon ($3x10^{13}$) [6]. Thus, the last remaining damping mechanism at the peak of Q(T) is identified as anchor damping.

ANCHOR DAMPING RESULTS

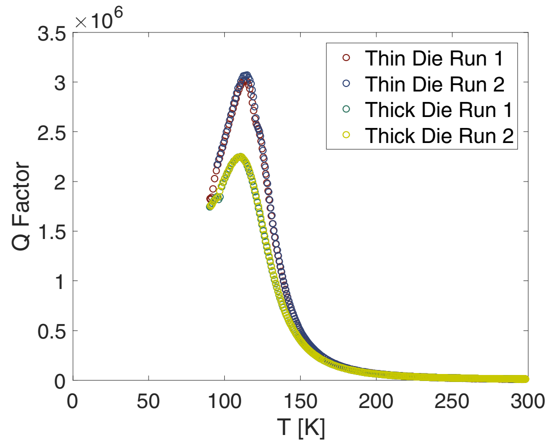

Figure 5: Quality factor vs. temperature of floated DETFs on thin and thick substrates.

With the identification of the peak Q(T) being an indicator of the amount of anchor damping, our experiments produce the surprising result that the thinned die apparently has less anchor damping than the thicker die when both are floated (Figure 5). This phenomenon is repeatable; the peak quality factor of the left and right DETF on the die same agree within 2% (see Figure 6). This observation of a relationship between anchor damping and die thickness for floated die experiments is our main result – We do not have a detailed explanation for this phenomenon, but we believe that the movement of energy through the anchor to the die and back to the resonator is an important factor in these studies. The thinner die affords less volume for storage of the energy, and therefore, provides less surface area and fewer other opportunities for the energy to be dissipated in the die, and also provides more opportunities for the energy to re-enter the resonator. This explanation is admittedly unsatisfactory, and we are

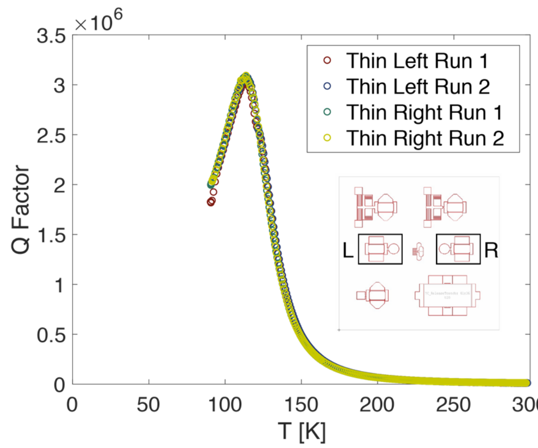

Figure 6: Left vs. right DETF floated on thin die. Top view of die with left (L) and right (R) DETFs.

working to experimentally investigate more variations in architecture and mounting to develop a better understanding. It is important to note that both of these substrates are thin compared to the wavelength for vibrations in Si at 1 MHz.

When the thin dies are pasted to the package, the anchor damping increases significantly, as seen in Figure 7, which could be caused by the increased stress felt by the thinner die, as well as by the introduction of new coupling mechanisms for the energy to escape the die.

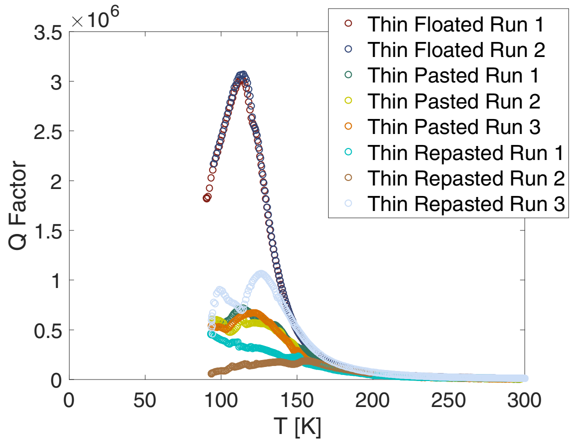

Figure 7: Quality factor vs. temperature of thin die pasted and floated.

In fact, the thinner die is more affected by an increase in anchor damping than the thick die by silver paste, 67% versus 38% (Figure 8). We see that the thick die has less anchor damping when pasted to the package than the thin die, indicating that the energy loss through the die attach is a significant loss mechanism for these resonators, compared to loss within the die. We are working to develop some scaling models for these observations.

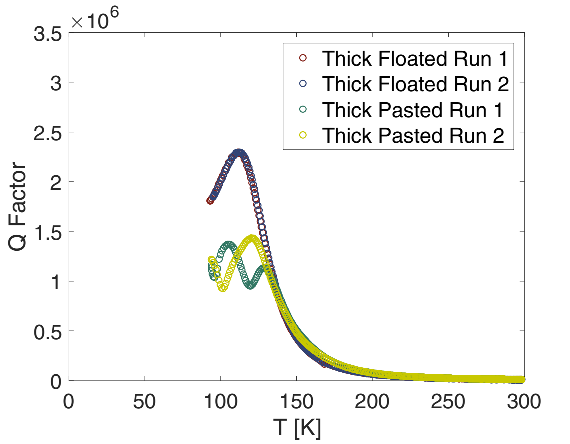

Figure 8: Quality factor vs. temperature of thick die pasted and floated.

CONCLUSION

In conclusion, thinning a die can decrease anchor damping in resonant MEMS devices as long as the die is not stressed by paste. This has implications for MEMS devices in small electronics or wearables where it is imperative to minimize device footprint and volume.

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REFERENCES

[1] D.K. Shaeffer, "MEMS Inertial Sensors: A Tutorial Overview", IEEE Communications Magazine, 51, 100 (2013).

[2] S. C. Mukhopadhyay, "Wearable Sensors for Human Activity Monitoring: A Review." IEEE Sensors Journal, 15, 3 (2015).

[3] J. Rodriguez, S. Chandorkar, G. M. Glaze, D. D. Gerrard, Y. Chen, D. Heinz, I. B. Flader, T.W. Kenny, "Direct Detection of Anchor Damping in MEMS Tuning Fork Resonators", J. Microelectromech. Syst, 23, (2018).

[4] G.D. Vukasin, J. Rodriguez, L. Comenencia Ortiz, G.M. Glaze, D.D. Gerrard, C.H. Ahn, Y. Yang, J. Lake, R.N. Candler, and T.W. Kenny, "Direct Measurements of Anchor Damping in Pressure-Limited Ring Resonators", Technical Digest of the 2018 Solid-State Sensor and Actuator Workshop, Hilton Head Isl., SC, 6/3-7/18, Transducer Research Foundation, Cleveland (2018), pp. 370-371.

[5] Y. Yang, Y.W. Lin, J. Rodriguez, G.D. Vukasin, D.D. Shin, H.K. Kwon, D.B. Heinz, Y. Chen, D.D. Gerrard, T.W. Kenny and A. Shkel, "On Decoupled Quantification of Energy Dissipation Mechanisms in Toroidal Ring Gyroscopes", Technical Digest of the 2018 Solid-State Sensor and Actuator Workshop, Hilton Head Isl., SC, 6/3-7/18, Transducer Research Foundation, Cleveland (2018), pp. 318-321.

[6] J. Rodriguez, S.A. Chandorkar, C.A. Watson, G.M. Glaze, C.H. Ahn, E.J. Ng, Y. Yang, and T.W. Kenny, "Direct Detection of Akhiezer Damping in a Silicon MEMS Resonator", Nature: Scientific Reports, 9, 1 (2019).

[7] C. Zener, "Internal friction in solids: II. General theory of thermoelastic internal friction," Physical Review, 53, 1 (1938).

[8] Y. Yang, E.J. Ng, Y. Chen, I.B. Flader, and T.W. Kenny, "A Unified Epi-Seal Process for Fabrication of High-Stability Microelectromechanical Devices", Journal of Microelectromechanical Systems, 25, 3 (2016).

[9] T. Middelmann, A. Walkov, G. Bartl, and Schödel, "Thermal expansion coefficient of single-crystal silicon from 7 K to 293 K," Physical Review B, 92, 17 (2015).

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