AN OVEN-CONTROLLED MEMS OSCILLATOR (OCMO) WITH SUB 10MW, ± 1.5 PPB STABILITY OVER TEMPERATURE

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ABSTRACT

This work presents a 20.2 MHz, 1.1 Million quality factor silicon MEMS resonator with sub 10mW ovenization power and ±1.5 ppb (parts-per-billion) frequency offset over 100 °C temperature range. This combination of ppb-stability, mm-scale size and mW power is unprecedented in the timing industry. The micro-oven design embedded within the fully encapsulated device layer provides excellent thermal isolation and low power operation while obtaining high yield and shock resistance. The control signal for oven is derived from the difference between the temperature coefficient of frequency (TCf) of dual modes within a single resonator body. This work exceeds the prior work [1] by improved heater design to < 2x better thermal isolation, signal conditioning and shock survivability without offset.

KEYWORDS

Microelectromechanical Devices, Microresonators, Temperature-Compensation, Ovenization.

INTRODUCTION

Most of modern electronics rely on a timing reference for operation. The quartz frequency standard has dominated this market due to the inherently low frequency-temperature dependence of certain crystal cuts [2]. As an alternative, silicon micromechanical resonators propose several advantages over the quartz counterpart; in particular the manufacturability using CMOS fabrication, much smaller footprint and tolerance to harsh environments such as shocks. However, the silicon MEMS resonator suffers from a severe TCf-induced thermal drift. An intrinsic silicon resonator will exhibit a TCf of about -30 ppm/°C due to the negative temperature coefficients of elastic moduli [3]. When uncompensated, the resonant frequency of a silicon resonator could shift over 3000 ppm over 100°C range, rendering it unusable for any precision timing reference applications.

Numerous compensation techniques have been studied to overcome this issue. Passive compensation such as heavily-doped silicon [4] or Si-SiO2 composite material [5] can suppress the TCf to a degree but to achieve cellular and communication grade performance, a better approach is necessary. Ovenization, where the resonator is controlled to a set temperature, is an active compensation technique that is a promising technique for achieving excellent temperature compensation.

An important consideration is the coupling between the size and mass of the ovenized element and the need for suspension stiffness that necessarily also brings increased thermal conductance between the heated element and the surroundings. In our work we have emphasized approaches that thermally control only the minimum essential element – the resonating body. This enables significant reduction in oven power and improvements in shock resistance.

For an ideal implementation, an accurate temperature measurement of the resonator is crucial. Several methods including the quality factor as a thermometer has been studied [6]. Our preferred method is measuring the resonant frequency itself since variations in external gain and offset do not impact the frequency measurement [7]. Previous work includes ovenization of a dual-mode MEMS resonator via joule heating in the encapsulation layer [8]. While the temperature stability improved significantly (up to ±200 ppb), the power consumption was relatively high (up to 200mW) due to the heat loss via the encapsulation layer. To mitigate this problem, the heater was moved into the device layer for improved thermal isolation [1, 7]. This device achieved a record-breaking stability result with silicon MEMS resonator while operating at less than 25mW and revealed a new possibility for OCXO application replacement. However, the aforementioned device had several issues of low yield and low bias voltage due to the device pull-in and still suffers from relatively high-power consumption. In this work, we demonstrate an oven-controlled MEMS oscillator (OCMO) with a high yield in our process, ultra-low power consumption (<10mW), better than OCXO level temperature stability and shock survivability up to 20,000g.

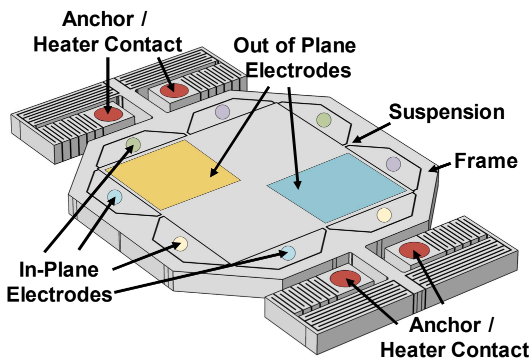

Figure 1: Schematic of the designed oven-controlled MEMS oscillator (OCMO). Joule current is flown between the two contacts on either side of the device. Dual-mode operation is achieved with the in-plane and out-of-plane electrodes.

DEVICE DESIGN

Figure 1 illustrates the design of the fabricated OCMO. The entire device is anchored on both sides of the device and the anchor also serves as contact for bias voltage and joule current flow. The serpentine beams provide both mechanical and thermal isolation as well as electrical heating via joule current. The frame that surround the device functions as a suspension for the resonant body (400µm x 400µm). By having the anchor/heater contact on both sides of the device, this design overcomes one of the biggest failure modes in MEMS fabrication that is the process stiction [9]. This device yielded ×2 better compared to a similar single-side anchor design by providing sufficient support during the release phase. Moreover, with the increased stiffness, this device can be DC biased above 10V without pulling in such that the capacitive feedthrough can be suppressed for the high frequency mode.

The device is fabricated on a 40µm p-type SOI (Boron doping concentration ~ 1.55e20 cm^{-3}) along <110> crystal orientation. To ensure the performance of the resonator, the device is sealed using a wafer-level polysilicon encapsulation. The *epi-seal* process, co-developed by Robert Bosch Research and Technology Center in Palo Alto and Stanford, provides ultra-clean cavity with low sealing pressure (~1Pa) for minimal damping and contamination-free environment. Moreover, the device benefits from a variant of the *epi-seal* process where no etch-holes were required to release bulk-type devices used in this study for high-Q resonators [10].

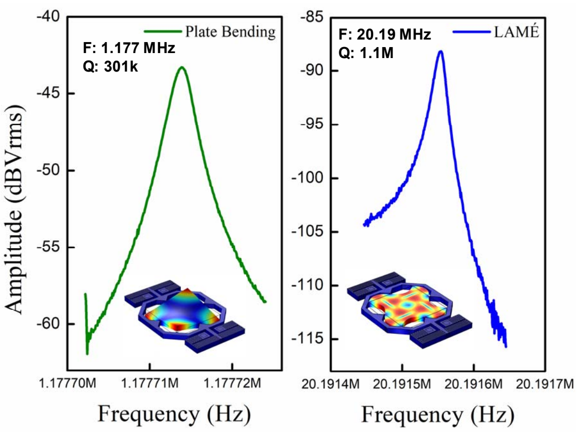

Figure 2: Mode shape, open-loop sweep frequency and the measured 3dB quality factor.

The mode shapes, frequencies and the quality factor are shown on Figure 2. As shown from the previous works, the two modes are sufficiently apart (×20 MHz) such that no significant mechanical coupling was observed [8].

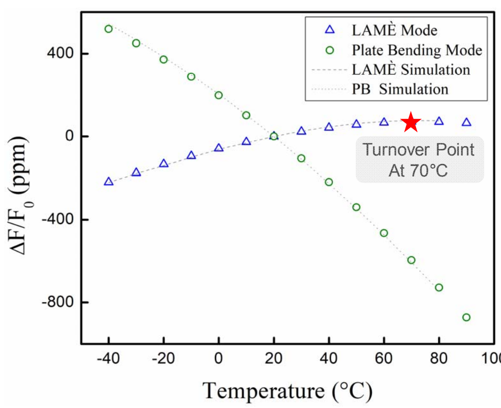

Figure 3: Frequency characteristics of the Lamé and the Plate Bending Mode under different ambient temperature. Dotted lines show the simulation results for the respective doping level.

The two modes exhibit the following uncompensated TCf characteristics shown in Figure 3. The Lamé mode exhibits a turnover point at 70°C as predicted from the TCf prediction model [11]. The ovenization point, therefore, is set to the turnover point in order to remove any first order temperature dependence of the resonator. The turn-over point can be tuned to specific applications via doping type and wafer orientation [4, 11].

EXPERIMENTAL METHOD

All of the experimentation was conducted in a temperature-controlled oven (accuracy ± 0.1 °C) with the die attached to a breakout PCB with a conductive paste. No additional packaging was done to the MEMS resonator. The additional electronics for the operation were set on the benchtop. For tracking the resonant frequencies of the two modes, they were locked in a closed phase-locked loop using Zurich Instrument HF2-LI lock-in as shown in Figure 4. The Lamé mode was operated in a differential configuration to further suppress capacitive feedthrough and amplify the signal [12].

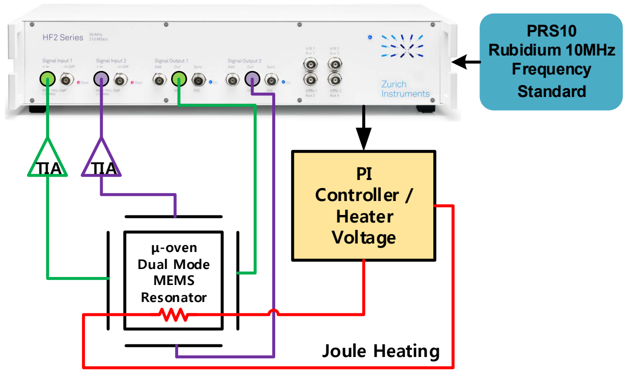

Figure 4: Experimental setup for this work. The resonant frequency was tracked with PLL and the heater voltage was controlled via a PI controller.

The frequency difference between the two modes were tracked using the lock-in and was fed to a controller as the error signal. As the frequency deviated from the target, a differential voltage ($\pm V_h$) is applied to the micro-oven to maintain the set frequency difference (and therefore the ovenization temperature) without perturbing the bias voltage. In order to minimize any temperature drift from the measurement system, a rubidium 10MHz frequency standard (Stanford Research System PRS-10) was used.

RESULTS

Ovenization Power

With the applied differential voltage to the electrodes, a joule current heats up the entire device. The surrounding frame ensures that the entire device is heated to the target temperature with minimal temperature gradient [13]. Figure 4 shows the frequency change of the two modes with different heater power in different ambient temperatures. The heater power consumption was calculated from the applied heater voltage and the current measurement in series to the loop. This result shows that under the lowest operating temperature (-40 °C), the ovenization power required to operate at the turn-over point is only 8mW which is more than 3X below the power used in the previous work [1].

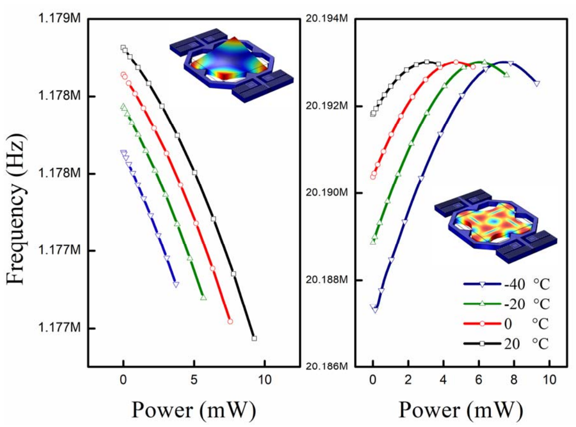

Figure 5: Frequency vs Heater power under different ambient temperature for both operational modes. At the lowest operating temperature, the ovenization only requires 8mW.

Temperature Stability

With the control loop in place, the device was exposed to a temperature ramps up/down of 6 °C/min for 10 hours to see how the system behaved in a transient response. The temperature scenario is shown on Figure 6 (a). As shown in Figure 6 (b), the controller maintained the setpoint by changing the heater voltage between 0.47V and 1.40V. The frequency offset of the Lamé mode remains within ±5 ppb range as seen in Figure 6 (c). This shows that the OCMO can retain an accurate frequency in severe temperature conditions. The spikes within the data could be due to imperfect controller parameters that can be further optimized in the future works.

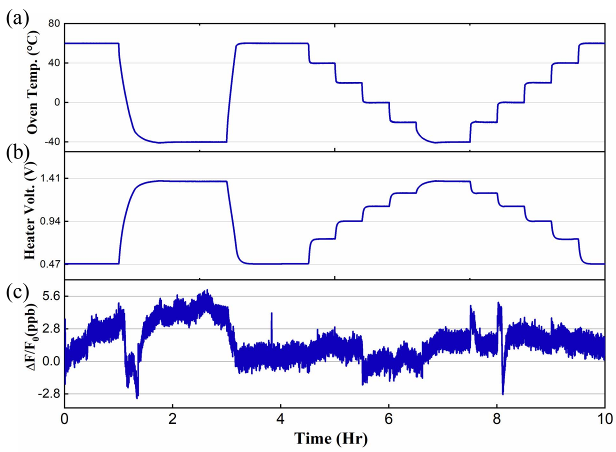

Figure 6: Real-time frequency measurements of the OCMO subjected to 6°C/min ambient temperature change. As the oven temperature ramps up and down, the applied heater voltage follows accordingly to maintain set temperature. The output frequency stability remains within ±5 ppb level.

Under a steady-state measurement, the OCMO performed beyond most available OCXO in terms of temperature offset. The data was measured while the control loop was running and oven temperature was ramped from -40°C to 60°C with 2 hour step interval. The mean frequency and 95th percentiles were studied at different ambient temperatures from -40 to 60 °C as shown in figure 7. Compared to the uncompensated MEMS resonator, the OCMO shows temperature stability improvement of up to 73,000× over the same temperature range. The results still show a residual temperature dependence especially pronounce between -10 and 0 °C and further analysis of the remaining drift source is necessary.

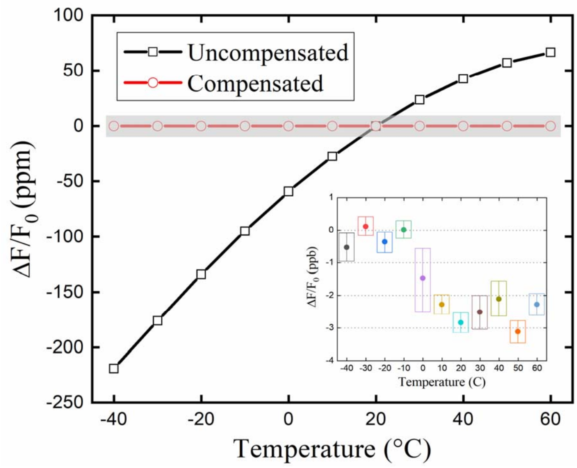

Figure 7: Steady-state Lamé mode frequency offset compared with the uncompensated result. Inset shows the statistical analysis of the result with the mean plotted with the circle with the 95th percentile envelope.

Allan Deviation

Another important characteristic of an oscillator can be studied with an Allan Deviation analysis. The OCMO was operating at 40 °C oven ambient for 20 hours and the results are shown in Figure 8. The floor is 9.3 e-11 around 10 second τ. With longer time scale, the long-term temperature fluctuation can be seen.

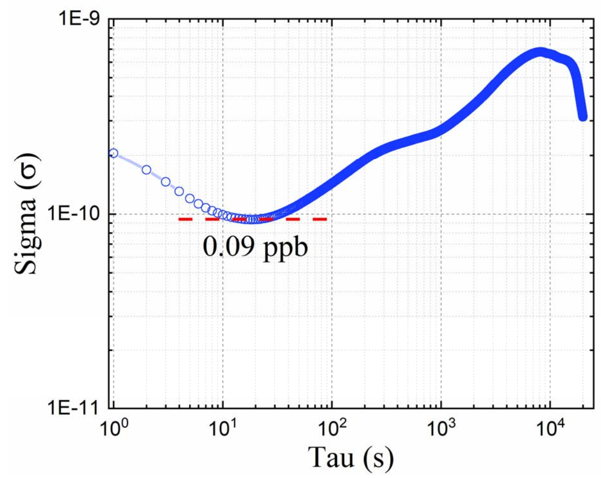

Figure 8: Typical Allan Deviation from 20hour test in 40°C ambient.

Shock Testing

The OCMO also has an advantage of the quartz counterpart in terms of shock survival. By testing on an in-house testing setup, the device survived shocks up to 20,000g with the results shown in Figure 9 [14]. Importantly, these devices survived 20,000g shock with no detectable change in properties and frequency offsets.

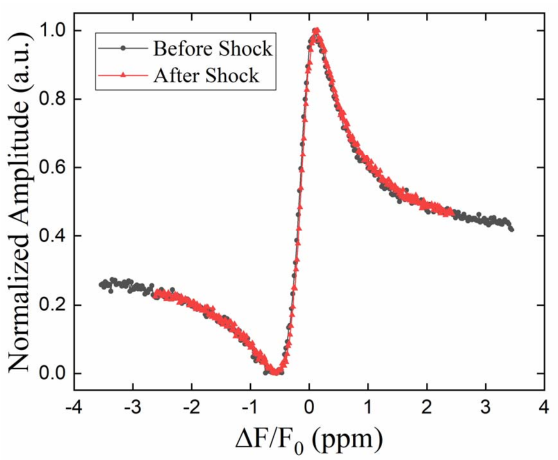

Figure 9: Open-loop frequency sweep of the Lamé mode before and after 20,000g shock testing.

CONCLUSION

In this work, we demonstrated an oven-controlled MEMS oscillator (OCMO) that can compete with the state-of-the-art OCXO. The dual anchor design allows low power (8mW) ovenization with robust yield, ppb temperature stability and extreme shock survivability. This combination of features is unprecedented in the entire timing industry.

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REFERENCES

[1] L. Comenencia Ortiz, H.-K. Kwon, J. Rodriguez, D. B. Heinz, Y. Chen, G. D. Vukasin, D. D. Shin, and T. W. Kenny, "A New Low Power MEMS Dual Mode Clock with PPB Stability Over Temperature", Solid-State Sensors, Actuators, and Microsystems Workshop, Hilton Head Isl., S.C., 6/3-6/7 (2018), pp. 90-91

[2] W. A. Marrison, "The evolution of the quartz crystal clock", Bell Syst. Tech. J., 27, 3 (1948)

[3] J.J. Hall, "Electronic Effects in Elastic Constants of N-Type Silicon", Physical Review, 161, 756 (1967)

[4] A. K. Samarao, and F. Ayazi, "Temperature Compensation of Silicon Micromechanical Resonators via Degenerate Doping", IEEE IEDM, Baltimore, M.D., 12/7-12/9 (2009), pp. 33.2.1-33.2.4

[5] B. Kim, R. Melamud, M. A. Hopcroft, S. A. Chandorkar, G. Bahl, M. Messana, R. N. Candler, G. Yama, and T. W. Kenny, "Si-SiO2 Composite MEMS Resonators in CMOS Compatible Wafer-scale Thin-Film Encapsulation", IEEE IFCS, Geneva, Switzerland, 5/29 – 6.1 (2007), pp. 1214 – 1219

[6] M. A. Hopcroft, B. Kim, S. Chandorkar, R. Melamud, M. Agarwal, C. M. Jha, G. Bahl, J. C. Salvia, H. Mehta, H. K. Lee, R. N. Candler, and T. W. Kenny, "Using the temperature dependence of resonator quality factor as a thermometer", Appl. Phys. Lett. 91, 013505 (2007)

[7] J. C. Salvia, 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", J. Microelectromech. S., 19, 1 (2010)

[8] Y. Chen, E. J. Ng, D. D. Shin, C. H. Ahn, Y. Yang, I. B. Flader, V. A. Hong, and T. W. Kenny, "Ovenized dual-mode clock (ODMC) based on highly doped single crystal silicon resonators", IEEE MEMS, Shanghai, China, 1/24-1/26 (2016), pp. 91-94

[9] D. B. Heinz, V. A. Hong, C. H. Ahn, E. J. Ng, Y. Yang, and T. W. Kenny, "Experimental Investigation Into Stiction Forces and Dynamic Mechanical Anti-Stiction Solutions in Ultra-Clean Encapsulated MEMS Devices", J. Microelectromech. S., 25, 3 (2016)

[10] E. J. Ng, Y. Yang, Y. Chen, and T. W. Kenny, "An Etch Hole-Free Process for Temperature-Compensated High Q, Encapsulated Resonators", Solid-State Sensors, Actuators, and Microsystems Workshop, Hilton Head Isl., S.C., 6/8-6/12 (2014), pp. 99-100

[11] E. J. Ng, V. A. Hong, Y. Yang, C. H. Ahn, C. L. M. Everhart, and T. W. Kenny, "Temperature Dependence of the Elastic Constants of Doped Silicon", J. Microelectromech. S., 24, 3 (2015)

[12] Y. Xu, and J. E.-Y. Lee, "Single-Device and On-Chip Feedthrough Cancellation for Hybrid MEMS Resonators", IEEE Tras. On Indus. Elec., 59, 12 (2012)

[13] H.-K. Kwon, D. B. Heinz, D. D. Shin, Y. Chen, L. Comenencia Ortiz, G. D. Vukasin, and T. W. Kenny, "Precise Local Temperature Measurement of Fully Encapsulated Ovenized MEMS Device", Solid-State Sensors, Actuators, and Microsystems Workshop, Hilton Head Isl., S.C., 6/3-6/7 (2018), pp. 358-361

[14] D. B. Heinz, V. A. Hong, Y. Yang, C.-H. Ahn, and Y. W. Kenny, "High-G (>20,000g) inertial shock survivability of epitaxially encapsulated silicon MEMS devices", IEEE MEMS, Las Vegas, N.V., 1/22-1/26 (2017), pp. 1122-1125

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