OVENIZED DUAL-MODE CLOCK (ODMC) BASED ON HIGHLY DOPED SINGLE CRYSTAL SILICON RESONATORS

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ABSTRACT

This work demonstrates, for the first time, ovenization of a fully-encapsulated dual-mode silicon MEMS resonator operational over a large ambient temperature range. We maintain a localized, elevated operating temperature by utilizing the temperature coefficient of frequency (TCf) difference between two excitation modes of the same resonant body as a thermometer, and by integrating a micro-oven in the encapsulation layer. Preliminary results of real-time compensation demonstrate a stability of ±250ppb of the in-plane Lamé-mode frequency over -20°C to 80°C.

INTRODUCTION

While silicon-based MEMS oscillators have gained great attention and commercial success as a replacement for quartz crystal oscillators over the past few years, further improvement in stability is still required for high precision applications due to limitations presented by the temperature dependence of frequency. The intrinsic temperature coefficient of elasticity (TCE) of silicon usually results in a linear temperature coefficient of frequency (TCf) of ~-30ppm/°C [1]. While passive compensation schemes, such as using highly doped silicon [2, 3] or composite materials [1, 4], can effectively reduce the temperature dependence of frequency without the need of external power, further active compensation is still required to achieve better stability.

Ovenization is an active compensation method that has shown great potential in achieving sub-ppm or ppb level frequency deviation over a large ambient temperature range [5-12]. This compensation scheme senses the device temperature and utilizes Joule heating to operate the resonators at a fixed, elevated temperature regardless of the ambient environment. To maintain the desired operating conditions with minimal control error, accurate measurement of the resonator temperature is essential. Various methods of device temperature sensing have been reported in the past. On-chip resistive thermistors are usually inaccurate in measuring the true local temperature due to errors arising from thermal gradients and stress effects [6]. Quality factor-based temperature sensing can measure the actual device temperature, however, this method is less repeatable and is easily impacted by any spurious modes [7]. Frequency-based sensing method has shown great potential in accurately measuring the device temperature. This sensing scheme is used in quartz oscillators known as Oven Controlled Quartz Crystal Oscillators (OCXO) [13], which achieve the highest frequency stability possible with a quartz crystal. This frequency detection method has also been adapted in MEMS resonators by operating resonators with two different TCfs on a single heating platform [8, 9]. In these

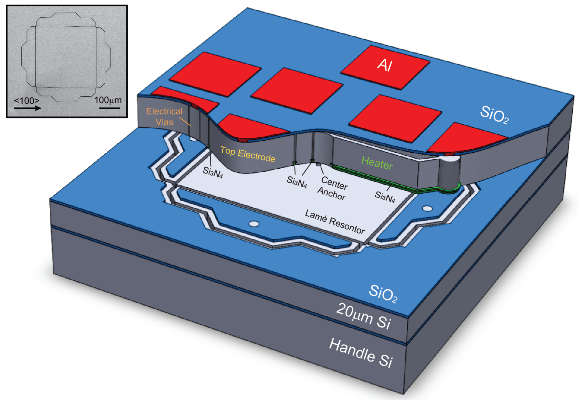

Figure 1: Schematic of the fully-encapsulated Lamé resonator which incorporates the functions of out-of-plane sensing and micro-ovenization in the encapsulation layer. And a top view SEM image of the Lamé resonator design.

examples, any thermal gradient between these two resonators lead to errors in estimating the true device temperature. To overcome this issue, a dual-mode temperature sensing scheme that measures the relative frequency of two different eigen-modes of a single resonator is preferred [14, 15]. This method, however, requires the engineering of two distinct TCf characteristics for two modes of a single resonator.

In this work, we demonstrate an ovenized dual-mode clock (ODMC) based on highly doped single crystal silicon resonators that utilizes the TCf difference between two modes that are excited on the same resonant body as a thermometer. Compared with other ovenization schemes that involve an extra thermometer or two separate resonant bodies, the dual-mode ovenization method eliminates any temperature gradients between resonators and thermometers, which in turn increases the overall stability over a large ambient temperature range.

DESIGN AND FABRICATION

The design of the ovenized dual-mode clock (ODMC) is illustrated in Figure 1. The resonant body is a 300µm x 300µm Lamé-mode resonator with a circular center anchor hanging from the encapsulation layer. Silicon nitride etch stops enable the integration of top electrodes for out-of-plane driving and sensing, as well as the micro-oven embedded in the encapsulation. The Lamé-mode resonator, in this case, can be simultaneously operated as a plate-bending-mode resonator. The device is fabricated in highly doped n-type (100) single crystal silicon (~6.2e19cm^{-3}) aligned with <100> crystal orientation. The doping type and concentration change the temperature dependence of the elastic constants of silicon, and in turn yield distinct TCf characteristics for the Lamé mode and

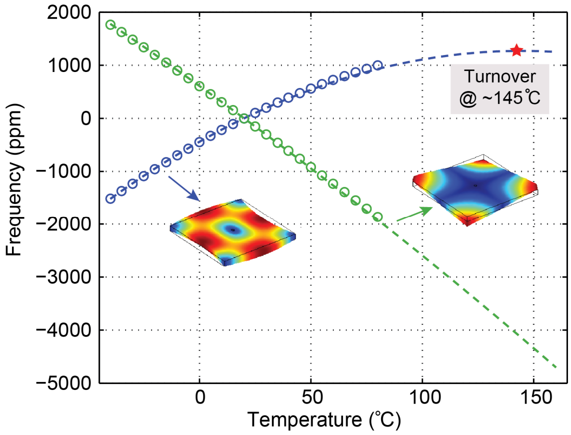

Figure 2: Temperature dependence of frequency of the two resonant modes as a function of ambient temperature for unheated devices. Dashed lines are simulation results for n-type 6.2e19cm^{-3} doping; circles are experimental data.

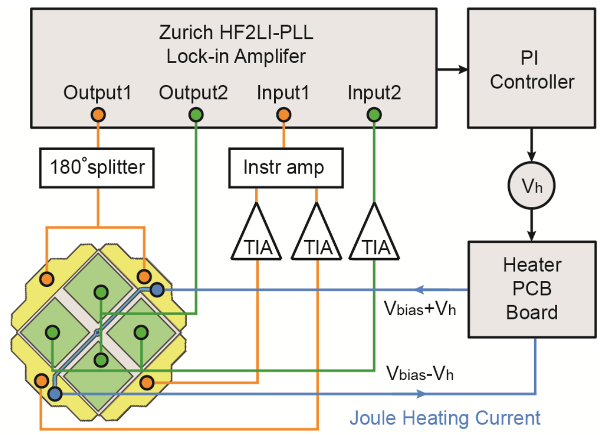

Figure 3: Block diagram of the experimental setup and control scheme. The frequency difference between the two modes (in ppm) serves as a thermometer for the feedback control. The in-plane electrodes are highlighted in yellow, top electrode regions in green, the cap heater in blue.

out-of-plane plate-bending mode as shown in Figure 2 [2]. A turnover temperature of the Lamé mode at about 145°C is an optimal operating temperature for better stability, control and noise performance.

The *epi-seal* encapsulation process was developed by a close collaboration between Robert Bosch Research and Technology Center in Palo Alto and Stanford University. While baseline process has been brought to commercial product by SiTime Inc., various improvements and extensions have been developed. The devices in this work are fabricated using a unified *epi-seal* fabrication process reported in [16]. The resonator is sealed in an 1100°C high temperature hydrogen environment by a layer of epitaxial silicon cap immediately after vapor HF releasing the device from the surrounding oxide. The high temperature hydrogen annealing process provides an ultra-clean, native-oxide-free device surface, while smoothing out the sidewall scallops through silicon migration. A near-vacuum cavity pressure (<1Pa) is achieved by diffusing out the residual hydrogen. The

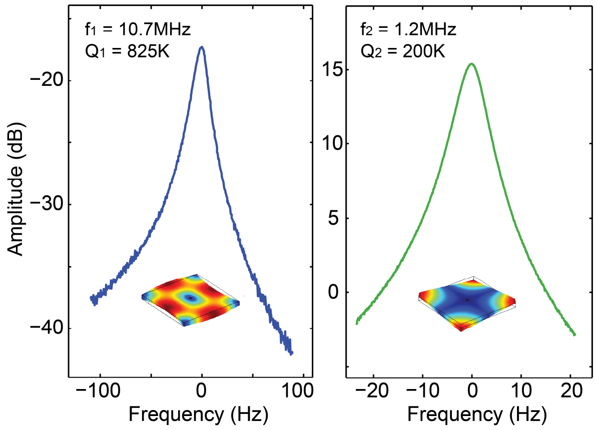

Figure 4: Open-loop frequency response of the Lamé mode (left) and the plate-bending mode (right). Signals are acquired after the instrumentation amplifier and the transimpedance amplifier (TIA).

accessibility of large releasing area without perforation holes in this process provides exceptional f×Q product for high performance resonators. Previous works have demonstrated no noticeable frequency drift, aging and fatigue over a year of testing [17, 18].

METHOD

In this proof-of-concept work, both Lamé and plate-bending modes are driven into resonance simultaneously using two phase-locked loops (PLL) in a Zurich Instrument digital lock-in amplifier. As shown in Figure 3, the Lamé mode is driven and sensed differentially through in-plane electrodes. Top electrodes defined in the encapsulation layer are used for the driving and sensing of the plate-bending mode. To maintain a constant device temperature, we implement a proportional-integral (PI) controller with ~14Hz control frequency. The control scheme uses the frequency difference of the two modes as a thermometer to adjust the Joule heating current that passes through the heater resistor located in the encapsulation layer. Bidirectional offset voltages (±V_h) are added to the bias voltage (V_{bias}) through the heater PCB circuit board and are applied to the two terminals of the cap heater. This ensures that the resonator is biased at constant voltage while the heating current changes. As a result, the control loop maintains a constant frequency difference (in ppm unit) between the two modes, which should indicate that the device is operating at a constant temperature.

One alternative is to use two oscillator circuits to drive both modes. A PLL-based feedback control loop is then used to phase-lock the two modes at a stable operating point where the resonator is heated to the desired temperature. This method has been demonstrated in both PCB and CMOS level circuits for two separated resonant body systems [8, 9] and can be easily adapted to the ODMC.

RESULTS

Open-loop Frequency Sweep

The open loop frequency sweeps at room temperature without any heating shows the frequencies of 10.7MHz and

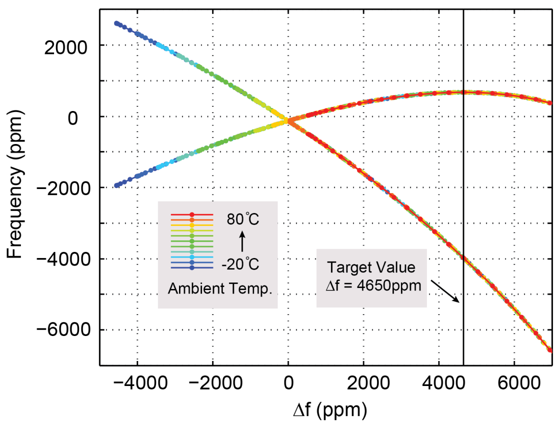

Figure 5: Frequencies of the two modes vs the frequency difference at different ambient temperatures and heating currents. Lamé mode $f_{1,ref}$ = 10.74MHz, plate-bending mode $f_{2,ref}$ = 1.187MHz, frequency difference $\Delta f = f_1/f_{1,ref} - f_2/f_{2,ref}$.

quality factor (Q) of 825k for the Lamé mode, and 1.2MHz and Q of 200k for the out-of-plane plate-bending mode (Figure 4). These two modes are an order of magnitude apart from each other, which ensures minimal mechanical coupling between the two modes.

Heating

For different ambient temperatures, the frequencies of both modes are tested as a function of heating voltage across the heater resistor, $V_{heater} = 2V_h$. Figure 5 shows the resonant frequencies of the two modes as a function of the frequency difference, Δf, when heating current increases at different ambient temperatures. Both modes follow their TCfs but start from the frequencies corresponding to the particular ambient temperature. All measurements lie along the same curve, which indicates that Δf is an accurate thermometer. Thus, by maintaining a constant Δf, the frequency output of the two modes will remain the same. As shown in the figure, a Δf value of 4650ppm is chosen as a point of operation, as it is the turnover temperature of the Lamé mode and thus gives the optimal control performance.

The resistance of the embedded micro-oven is ~200Ω. A heating voltage of 10.2V can heat the device to its turnover temperature of 145°C at an ambient temperature of -20°C. The overall Joule heating power consumption is estimated to be ~0.3°C/mW when the device is hard attached to the package with silver paste. Better thermal insulation can be incorporated in future designs to minimize the power consumption.

Stability with Closed-loop Control

The proposed control scheme is used to maintain a constant target Δf value of 4650ppm between the two modes. Figure 6 shows the steady-state Lamé mode output frequency as a function of ambient temperature. The ovenization improves the frequency stability by over 4000x when compared with uncompensated frequency deviation (>2000ppm) over the ambient temperature range of -20°C to 80°C. A repeatable residual temperature dependence of frequency of 500ppb is shown, which may be caused by stress effects.

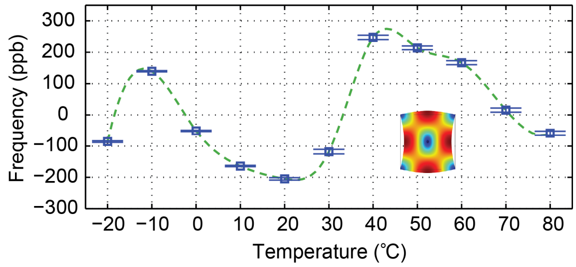

Figure 6: Measurement of steady-state Lamé mode frequency deviation of the ODMC operating at the target Δf = 4650ppm.

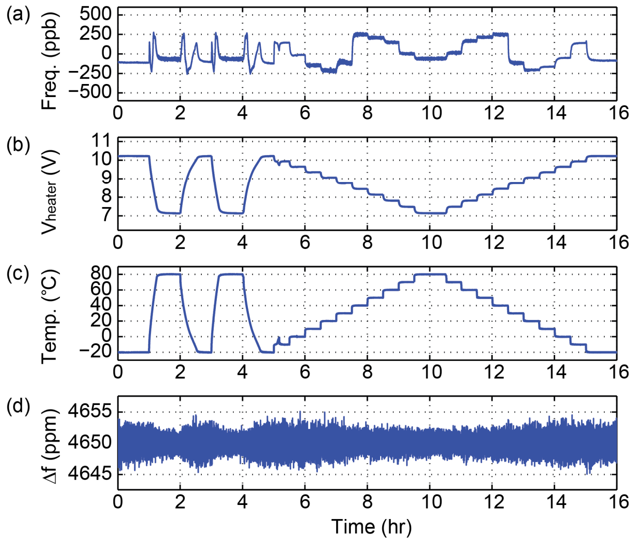

Figure 7: (a) Real-time frequency measurement of the ODMC subject to 6℃/min ambient temperature ramps; (b) Voltage across the heater resistor; (c) Ambient temperature; (d) Frequency difference between the two modes

Furthermore, real-time frequency measurements of the ODMC subject to 6°C/min ambient temperature ramps over -20~+80°C are shown in Figure 7. Measured frequency deviates within a range of ±250ppb, showing sufficient control capability. More importantly, no frequency drift or hysteresis is observed during temperature ramps over a testing period of 16 hours. Figure 8 shows an approximate Allan Deviation curve, which reaches a minimum deviation of about 6ppb at 100s when the device is operating at -20°C with ±0.3°C temperature fluctuation over time.

CONCLUSION

Demonstrated in this work is an ovenized dual-mode clock (ODMC) that utilizes the dual-mode temperature sensing scheme and micro-oven heating with a closed control loop to actively compensate the temperature dependence of resonant frequency. Preliminary results of real-time frequency compensation achieve a frequency stability of ±250ppb over -20~+80°C and over a time range of 16 hours without frequency drift or hysteresis. This work shows the potential of ODMC for high-precision applications. Future work will target better thermal

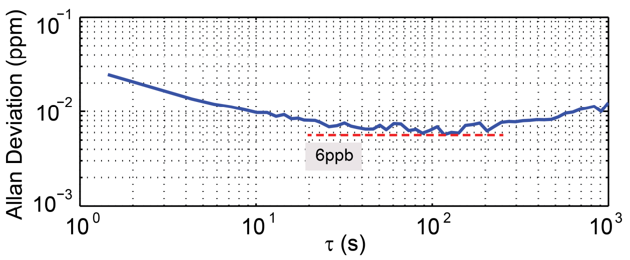

Figure 8: Approximate Allan Deviation for the ODMC

isolation, lower power consumption, less stress effects, and a more refined controller for the system.

ACKNOWLEDGEMENTS

This work was supported in part by the Defense Advanced Research Projects Agency Precision Navigation and Timing Program managed by Dr. A. Shkel and Dr. R. Lutwak under Contract N66001-12-1-4260, and in part by the National Science Foundation through the National Nanotechnology Infrastructure Network under Grant ECS-9731293. We appreciate the benefit of regular conversations about high-stability time references with Dr. John Vig. Y. Chen is supported by a Stanford Graduate Fellowship.

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