

A TEMPERATURE-STABLE MEMS OSCILLATOR ON AN OVENIZED MICRO-PLATFORM USING A PLL-BASED HEATER CONTROL SYSTEM

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ABSTRACT

In this work, an oxide-refill process is used to null the first-order temperature coefficient of frequency (TCF) of silicon MEMS resonators and to achieve high thermal resistance isolation structures. The technology enables fabrication of a low-power ovenized micro-platform on which multiple MEMS devices can be integrated. The intrinsic frequency-temperature characteristic of two resonators is utilized for temperature sensing, and closed-loop oven control is realized by phase-locking two MEMS oscillators at a specific temperature. PLL-based control circuitry is implemented in 0.18 μm CMOS to interface with the MEMS resonators. The ovenized MEMS oscillator exhibits an overall frequency drift of ± 5.5 ppm over -40 $^{\circ}\text{C}$ to 70 $^{\circ}\text{C}$. The MEMS oscillator exhibits near zero phase noise degradation in closed-loop operation.

INTRODUCTION

Because of the intrinsic temperature coefficient of elasticity (TCE) of silicon, an uncompensated moderately doped silicon micromechanical resonator shows a linear TCF of ~ 30 ppm/ $^{\circ}\text{C}$ [1], which typically dominates the environmentally induced frequency drift of a silicon MEMS oscillator. This relatively large TCF needs to be compensated when making silicon-based timing units or resonant-type physical sensors. One solution is to actively change the frequency of the resonator to compensate for environmental changes. For tight control of the frequency, this method requires accurate monitoring of the resonator temperature. Techniques utilizing a resistive temperature detector on chip are inaccurate in estimating the true local temperature of the resonator [2]. Among other sensing methods, frequency-based temperature sensing has been used in quartz crystal references with excellent accuracy [3]. Such a frequency detection method has also been adopted in miniature MEMS timing units by engineering the TCF values of two resonators with a common thermal isolation structure and heating only the two resonators to achieve stable operation [4]. Using self-sensing method based on frequency drift of the MEMS resonator, excellent stability has been demonstrated for ovenized MEMS oscillators. However, when employing a frequency-based sensing method on two thermally isolated resonators, the need for having controlled TCF and high thermal isolation to the platform sets additional constraints on the resonator design, making it challenging to simultaneously achieve high- Q , low resistance, and high thermal isolation.

In this work, we study a different approach in implementing ovenized silicon MEMS oscillators. A general-purpose thermally isolated micro-platform is implemented, inside which multiple micro-devices can be

integrated. The platform does not add any constraint to the design of individual devices on the platform. The active compensation concept is sketched in Figure 1. Two MEMS resonators in a thermally isolated platform are designed to have different frequency drift characteristics as the temperature of the platform changes. The TCF values of the resonator dominate the frequency-temperature characteristic of the oscillators. To null the TCF of the output frequency, the feedback control signal is extracted from the phase offset between the two MEMS oscillators in a phase-locked loop (PLL). In the PLL circuitry, the oscillators are locked into a stable operating point, where the MEMS resonators are heated to a desired oven-set temperature. This way, the oscillators are stabilized regardless of external temperature variations. The control loop also stabilizes the temperature of the whole micro-platform, which favors integration of other devices (such as gyroscopes and accelerometers) for temperature-stable operation.

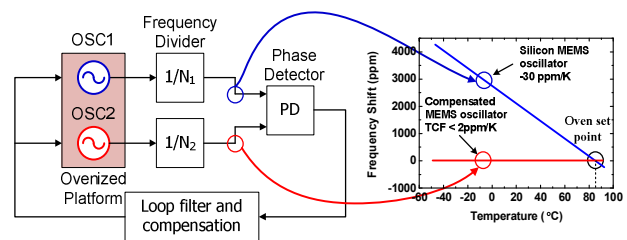


Figure 1: Principle of using two MEMS resonators on an ovenized platform to realize oscillators, temperature sensing, and closed-loop oven-control.

MEMS PROCESS FOR THERMAL ISOLATION AND TCF-COMPENSATION

The frequency-based temperature sensing method requires two MEMS resonators with different TCF values. The TCF of silicon resonators can be engineered by including silicon dioxide-refilled trenches in areas of high strain energy density [5]. This technique is adopted to fabricate a passive TCF-compensated resonator having zero first-order TCF simultaneously with an uncompensated resonator. The oxide-refilled trenches or islands benefiting from low thermal conductivity of silicon dioxide ($1.3 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$) are also ideal for fabricating thermal isolation structures. Embedding oxide islands in silicon structures results in substantial reduction of the overall thermal conductivity (thermal conductivity of silicon is $131 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$) and thus the power consumption for ovenization.

Oxide islands are formed by silicon deep reactive ion etch and a subsequent oxide-refill process (Figure 2). The process adopts the steps in fabricating TCF-compensated piezoelectric-on-silicon MEMS resonators [5]. Silicon-on-insulator (SOI) wafers with a $20 \mu\text{m}$ thick high-resistivity

(>1000 $\Omega\cdot\text{cm}$) device layer are used. A scanning electron microscope (SEM) image of a fabricated micro-platform is shown in Figure 3. The platform includes two MEMS resonators as a proof-of-concept; more devices can be integrated on the same temperature-stable platform. The active area incorporating a built-in metal heater and two resonators is supported by four thermal isolation legs. A cross-sectional view of the fabricated oxide-refilled structures is shown in Figure 3.

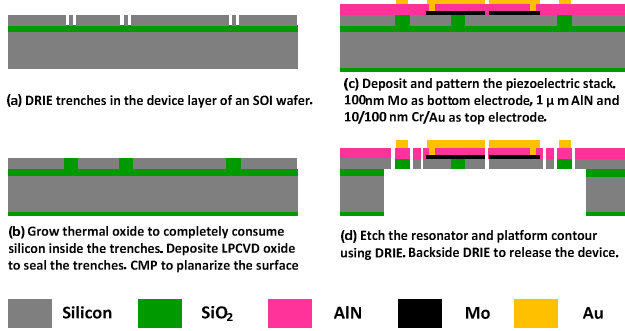


Figure 2: Process flow for fabricating temperature-compensated resonators on a thermal isolation platform.

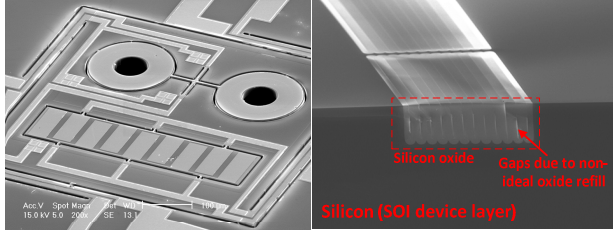


Figure 3: Left: An SEM image of a MEMS platform, which includes two resonators; Right: A cross-sectional SEM of an oxide island formed using the process.

HIGH PERFORMANCE RESONATORS ON A MICRO-PLATFORM

Both an uncompensated and a TCF-compensated resonator are fabricated on the platform to realize the PLL-based oven control. For the uncompensated AlN-on-Si resonator, a 9th-order length extensional mode bulk acoustic resonator (LBAR) has been designed (Figure 4).

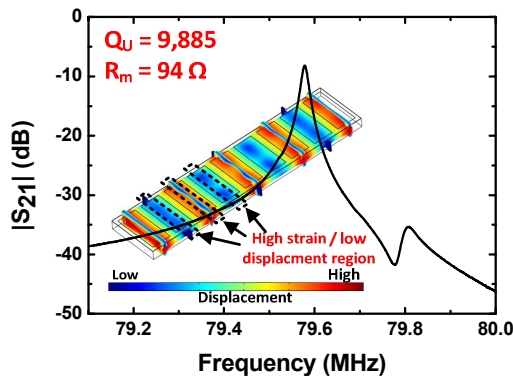


Figure 4: Measured response of an uncompensated 9th-order length extensional mode resonator (LBAR).

Nine electrodes are patterned to cover the high stress regions for proper piezoelectric coupling. Six tethers are located on the nodal points to minimize anchor loss and

provide robust support. The measured frequency response of the LBAR is shown in Figure 4. The unload- Q (Q_U) of this vibration mode is extracted as 9,885 ($f \times Q \sim 8 \times 10^{11}$). The resonator exhibits a low insertion loss of 8.6 dB, indicating a low motional impedance of 94 Ω .

For the TCF-compensated resonator, a coupled-ring resonator design is adopted from [5]. Oxide islands are embedded inside two vibrating rings. The measured response of the coupled-ring resonator is plotted in Figure 5, showing the resonance mode near 19.2 MHz. This coupled-ring resonator exhibits a Q_U of 7,354 ($f \times Q \sim 1.4 \times 10^{11}$) and a motional impedance of 443 Ω . As shown in Figure 6, the extracted TCF of the resonator is +5 ppm/K near the desired oven-set temperature ($\sim 90^\circ\text{C}$). The turn-over point (maxima of the parabolic curve) is near 190°C . The over-compensation can be reduced by improving the design and the fabrication control.

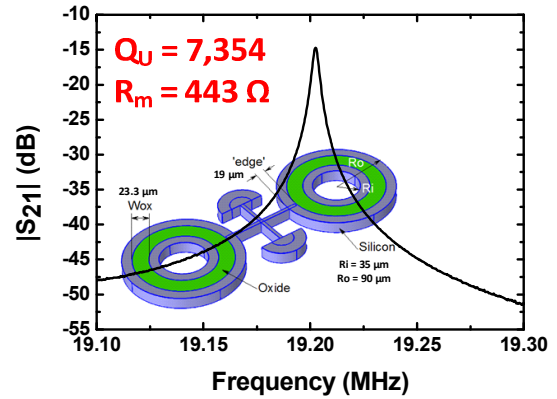


Figure 5: Schematic of a 19.2 MHz TCF-compensated coupled-ring resonator.

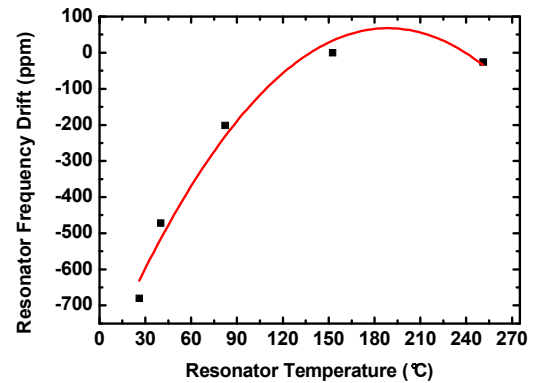


Figure 6: Measured frequency shift of the 19.2 MHz coupled-ring resonator with temperature (fitted to a second-order polynomial curve).

THERMAL PROPERTIES OF THE MICRO-PLATFORM

The oxide-refill process is also used to implement high thermal resistance support structures for the platform. The top view of a thermal isolation leg attached to a square-shape platform is sketched in Figure 7. Oxide islands are embedded in the supporting legs of the platform, as highlighted. Using oxide islands, the legs can be designed with high thermal resistance while having sufficient stiffness. Also, wide supporting legs allow routings of multiple low-resistance electrical connections

using a thin-film metal layer, which is favorable for integrating multiple devices on the platform. The effective thermal resistance from the platform center to the external thermal boundary is measured to be ~ 13.4 K/mW at ~ 1 mTorr ambient pressure $\square$ an improvement of $22\times$ compared to an all-silicon design (Figure 7) $\square$ allowing for low-power ovenization (in mW range) in a typical MEMS package.

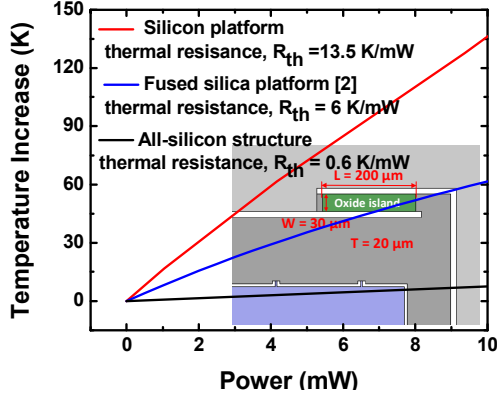


Figure 7: Temperature increase of the platform active area (red line) vs. heater power extracted from measurement. Results are compared to a fused silica platform [2] (blue line) and a silicon platform without oxide islands (black line). The inset shows dimensions of the thermal isolation leg.

The thermal property can be modeled using an RC equivalent circuit as shown in Figure 8. In the equivalent circuit model, the thermal resistance introduced by the isolation legs of the platform is represented by a resistor, $R_{th,leg}$. Also, $R_{th,RES1}$ and $R_{th,RES2}$ model the thermal resistances of the coupled-ring resonator and LBAR, respectively. Heat capacity (thermal mass) of a solid structure is modeled using capacitors. In Figure 8, capacitor C_{pl} models the heat capacity of the large platform and two capacitors, C_{RES1} and C_{RES2} , model the heat capacity of the resonators on the platform.

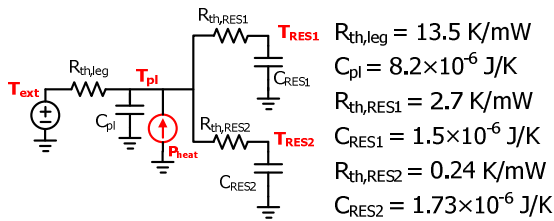


Figure 8: A simplified thermal model for the micro-platform and two resonators.

PLL-BASED OVEN CONTROL SYSTEM

The design of the PLL-based oven-control system can be studied using a linear control model sketched in Figure 9. In this model, temperature-induced frequency drift of two oscillators are modeled with coefficients, TCF_1 and TCF_2 , respectively. Values of TCF_1 and TCF_2 transduce temperature in the thermal domain to frequency domain signals. Using programmable frequency dividers, the divided-down frequencies of the two oscillators are configured to be matched at the desired oven-set temperature. A phase-frequency detector (PFD) detects

the phase or frequency difference, and the average voltage output from the PFD indicates phase offset in lock. The phase offset information translates into a control signal to heat the platform to the oven-set temperature. The heater driver is designed using a square-root generator to linearize the transfer characteristic from the control voltage (V_{CTRL}) to the heater power (P_{heat}). Using such a design, the PLL can be treated as a linear control system, and the loop gain is near constant regardless of the operating point [2]. The analog square-root generator circuit is designed using CMOS translinear circuits [6].

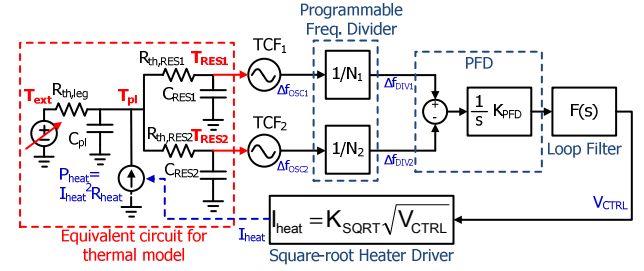


Figure 9: Linear model for the PLL using two MEMS oscillators for temperature sensing and oven-control.

The PLL is designed to have two integrators in the loop (type-II PLL), including one integrator from the PFD and another integrator in the loop filter. Such a design ensures a high DC loop gain to eliminate static errors. However, the feedback loop is potentially unstable with two integrators and a thermal pole ($f_{pl} = 1/2\pi R_{th,leg} \cdot C_{pl}$) at low frequencies. In this work, a special loop filter design with two compensation zeroes is employed. Two zeroes are used to cancel out the low frequency thermal pole (f_{pl}) and create a phase margin at the unity-gain frequency (Figure 10). Therefore, by strategically placing the frequency of zeroes, the loop dynamics can be defined to be independent of the thermal pole frequency. In this prototype design, the control system has a unity-gain bandwidth of more than $10\times$ the thermal pole frequency (f_{pl}), which indicates the control loop can respond fast to correct any dynamic error.

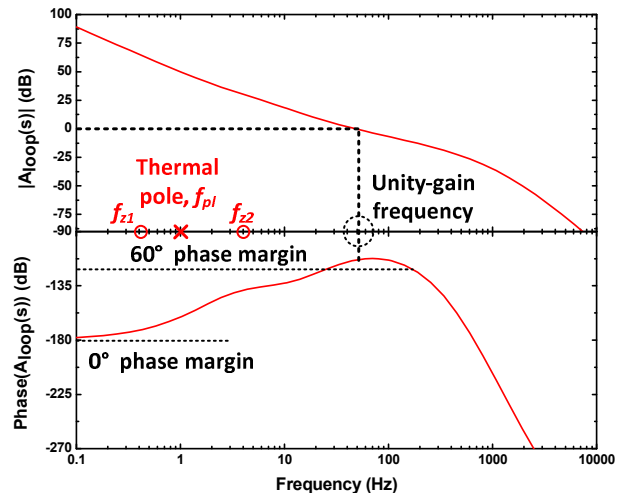


Figure 10: Loop gain of the temperature controller with two compensation zeroes on a Bode plot; the system has two integrator, a low-frequency thermal pole (f_{pl}), and two compensation zeroes (f_{z1} and f_{z2}) from the loop filter.

MEASUREMENT RESULTS

The CMOS PLL circuitry for the oven-control system is implemented using TSMC 180 nm CMOS technology. In measuring the prototype system, the CMOS chip and the MEMS chip are mounted separately in ceramic packages, and the packages are assembled on a PCB. The frequency stability of MEMS oscillators under external temperature change is measured. During the measurements, the PCB containing both the MEMS chip and the CMOS chip is placed in a vacuum chamber with a pressure level of less than 10 mTorr. The chamber temperature is swept from -40°C to 70°C while the output frequency of the MEMS oscillators in the PLL is monitored using a frequency counter (Agilent 53181A). The chamber temperature ramp is a relatively slow process and the PLL-based oven control system loop has a sufficiently large bandwidth. Therefore, the two oscillators used for active compensation are locked during the chamber temperature ramp. As a result, the frequency counter records identical frequency outputs from the oscillators. The frequency stability of the MEMS oscillators on the micro-platform is measured when the PLL-based oven-control system is active. The frequency drift of the MEMS oscillators is recorded and plotted in Figure 11. The oscillator has an overall frequency drift of ± 5.5 ppm over the chamber temperature of -40 to 70°C . Recalling that an uncompensated silicon MEMS oscillator has a TCF of -30 ppm/ $^{\circ}\text{C}$, the oven-control regulates the temperature fluctuation of the uncompensated resonator on the platform to within $367\text{ m}^{\circ}\text{C}$.

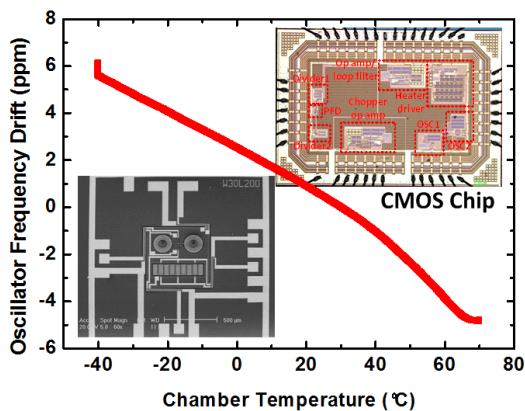


Figure 11: Measured output frequency drift versus temperature (inset shows microscopic photographs of the MEMS chip and the CMOS chip for the PLL-based control system).

The phase noise when the oscillator is in the PLL for ovenized operation is measured and compared to the phase noise when the MEMS oscillator is free running in Figure 12. It can be seen that the PLL-based active compensation does not degrade the far-from-carrier noise, while the measured close-in-carrier phase noise is even improved. In the phase noise measurement using an Agilent E5500 system, a frequency scan of the close-in-carrier region (offset frequency in the range of 1-100 Hz from carrier) takes approximately 5-10 s to complete. In such measurements, slow frequency fluctuations due to temperature variations cannot be distinguished from 1/f

noise in the measured phase noise plot. In fact, slow temperature variations tend to dominate the fluctuations in the close-in-carrier region. When the MEMS oscillator is placed in the PLL, the active compensation loop effectively regulates temperature variations of the MEMS resonator. Therefore, we observe improvement in the phase noise when MEMS oscillators are in the PLL-based active compensation system.

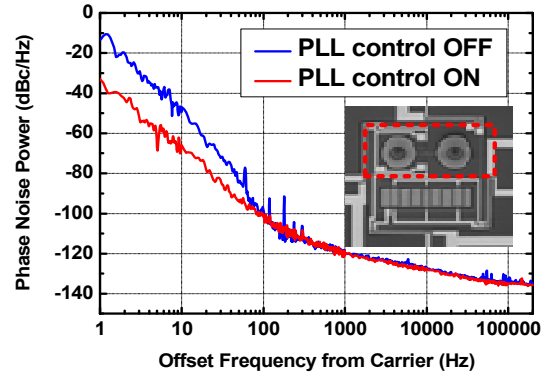


Figure 12: Measured phase noise performance of the 19.2 MHz MEMS oscillator using a TCF-compensated coupled-ring resonator on the platform. The phase noise performance with PLL-based compensation is compared to the same free-running oscillator performance.

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