TRI-MODE OPERATION OF HIGHLY DOPED SILICON RESONATORS FOR TEMPERATURE COMPENSATED TIMING REFERENCES

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ABSTRACT

In this work, we propose a novel temperature compensation method that utilizes a tri-mode operation scheme to generate a temperature-stable frequency reference over a large temperature range. Three resonant modes are excited simultaneously on a highly doped silicon MEMS resonator, and the unique TCf characteristic of each mode is fitted to a parabolic curve. A linear combination of the three frequencies is shown to eliminate the temperature dependence up to second order and produce a temperature-insensitive frequency output. Preliminary results verify the concept and show a ±14ppm temperature dependence of the output frequency across the temperature range of -40~80°C.

INTRODUCTION

Silicon MEMS resonator-based timing references, as an alternative to quartz crystal resonators, has been an active research topic for more than 50 years and has recently gained significant commercial successes [1]. While there are many remaining challenges, one consistent goal of silicon MEMS resonator research has been to minimize the temperature dependence of the resonant frequency, given that the intrinsic temperature coefficient of elasticity (TCE) of silicon usually results in a linear temperature coefficient of frequency (TCf) of -30ppm/°C. Thus, temperature compensation is essential for achieving highly stable timing references with silicon MEMS resonators for applications such as timekeeping, inertial measurement or communication.

Active compensation schemes reduce the temperature dependence of frequency by actively tuning the output frequency according to the actual temperature. Closed-loop feedback control or open-loop frequency tuning based on look-up tables are usually used. Previous work has shown the implementation of ovenization [2-4], electrostatic tuning [5, 6] or variable frequency multiplication [7] based on various temperature sensing techniques. Although active compensation methods have been shown to achieve a low frequency drift over a large temperature range, they come at the cost of high power consumption and require more sophisticated control/tuning schemes.

On the other hand, passive compensation methods involving the use of composite materials [8, 9], doping [10, 11], variable gaps [12] or stress [13] do not require external power for frequency tuning, but usually show a substantial second-order temperature dependence of frequency due to the nature of the compensation mechanism.

Circuit compensation techniques, which lie between active and passive compensation schemes, have been previously reported [14, 15]. Temperature insensitive output frequency is synthesized by using two or more frequencies that have different temperature dependence to cancel out the temperature effect. Compared with the aforementioned active compensation methods, circuit compensation techniques require no temperature sensor or active control scheme. Multiple frequencies are mixed with basic circuits to synthetize and produce the compensated output frequency. Previously reported efforts, however, only use two distinct modes and are able to cancel out just the first order temperature dependence [14], or utilize three separate resonators [15], resulting in a large device footprint and possible error due to temperature gradients.

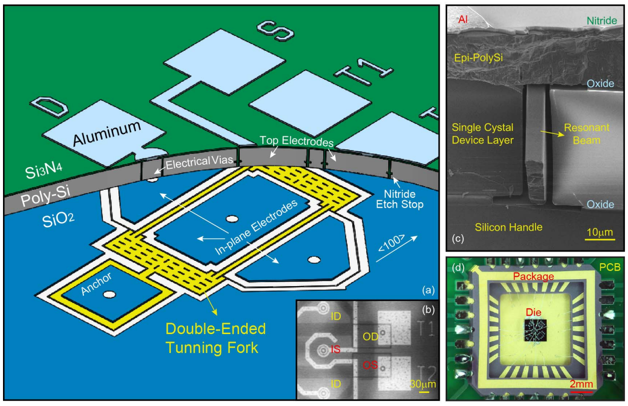

Figure 1: (a) Cutaway schematic of an epi-seal encapsulated DETF resonator with top electrodes that allow sensing of out-of-plane resonant modes. (b) IR image of the device showing in-plane drive (ID) and sense (IS) electrodes, and out-of-plane drive (OD) and sense (OS) electrodes. (c) SEM cross-section image of the encapsulated resonator beam. (d) Epi-sealed resonator die wire-bonded to a gold package on a PCB breakout board.

Utilizing three resonant modes on a single hermetically encapsulated silicon MEMS resonator, this work proposes a multi-frequency system for generating a temperature-stable frequency reference with no temperature dependence up to second order.

DESIGN AND FABRICATION

In this work, we demonstrate a tri-mode compensation scheme with double-ended tuning fork (DETF) resonator (Figure 1) made in highly doped silicon. The device is fabricated with a 40μm-thick (100) silicon-on-insulator (SOI) wafer using the *epi-seal* encapsulation process developed by Robert Bosch Research and Technology Center in Palo Alto and Stanford University [16]. The process enables a wafer-scale encapsulation with a high-vacuum, ultra-clean, oxygen and humidity free cavity environment, allowing for high quality factor (Q) and high stability resonators [17].

As shown in Figure 1, in this work, the single anchored DETF resonator is fabricated along <100> crystal orientation in highly doped n-type single crystal silicon with phosphorus dopant (~0.32mΩ-cm resistivity).

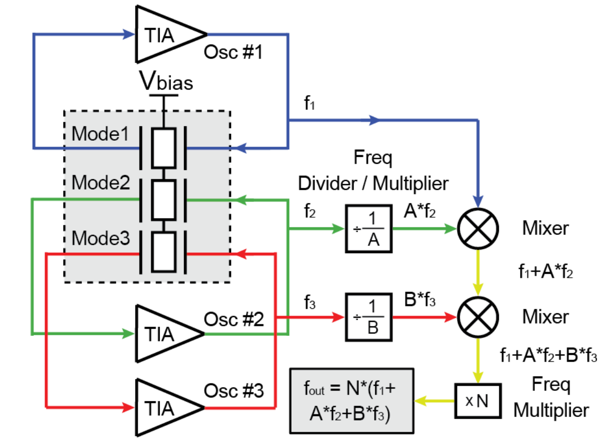

Figure 2: Algorithm for generating temperature compensated timing reference by simultaneously oscillating three modes with unique TCfs on a single resonant body. Fractional-N PLL is used as the frequency multiplier. Frequency summing and subtracting are achieved with a mixer and suitable filters.

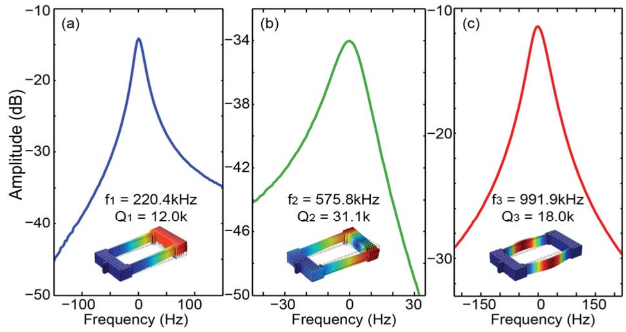

Figure 3: Open loop frequency sweeps of the three resonant peaks at room temperature. Insets show the three mode shapes, nominal frequencies and quality factors.

The two beams, 116µm apart from each other, are mechanically linked through a coupling mass at each end. The beams are identical in dimension: 6µm wide and 200µm long. Silicon nitride etch stops are embedded in the encapsulation layer to allow the integration of top electrodes for out-of-plane capacitive driving and sensing. An infrared (IR) image of the device (Figure 1b) shows the location of drive and sense electrodes for both in-plane (IP) and out-of-plane (OOP) resonant modes, respectively. A cross-section SEM image (Figure 1c) shows one of the resonant beams encapsulated with a poly-silicon cap. As shown in Figure 1d, after dicing, the device can simply be hard-attached and wire-bonded to a gold package on a printed circuit board for subsequent testing in ambient environment.

METHOD

As detailed in previous study [10], heavy doping modifies the temperature dependence of the elastic constants of single crystal silicon and in turn yields distinct resonant TCf characteristics, which also depend on mode shape and crystal orientation. Here, we demonstrate that three resonant modes can be simultaneously excited on one single resonant body and show the linearly independent

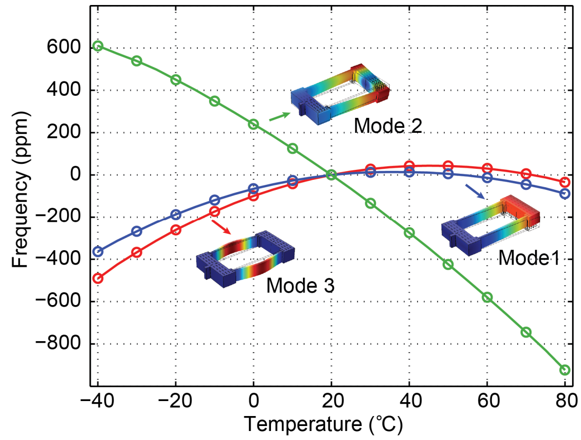

Figure 4: Temperature dependence of frequency of the three resonant modes. Unique TCf curve is shown for each resonant mode.

TCf for each mode. Then, the frequencies of the three resonant modes can be used to synthesize a temperature insensitive output frequency.

Consider a system in which three frequencies exhibit unique parabolic dependence with temperature. Each of the frequencies can then be expressed as:

$$f_i = \alpha_i T^2 + \beta_i T + f_{i,0} \qquad (1)$$

where $i = 1, 2, 3$ and T represents temperature.

Here, we can in theory generate a temperature independent output frequency that is a linear combination of the three input frequencies, shown below:

$$f_{out} = f_1 + Af_2 + Bf_3 \qquad (2)$$

Combine Equation (1) and (2):

$$\begin{aligned} f_{out} = {} & (\alpha_1 + A\alpha_2 + B\alpha_3)T^2 + \\ & (\beta_1 + A\beta_2 + B\beta_3)T + \\ & (f_{1,0} + Af_{2,0} + Bf_{3,0}) \end{aligned} \qquad (3)$$

To eliminate both first and second order temperature dependence of the output frequency, coefficients A and B need to satisfy both $\alpha_1 + A\alpha_2 + B\alpha_3 = 0$ and $\beta_1 + A\beta_2 + B\beta_3 = 0$. This allows for evaluation of the optimal values for the coefficients A and B:

$$A = \frac{\alpha_3\beta_1 - \alpha_1\beta_3}{\alpha_2\beta_3 - \alpha_3\beta_2}, \quad B = \frac{\alpha_2\beta_1 - \alpha_1\beta_2}{\alpha_3\beta_2 - \alpha_2\beta_3} \qquad (4)$$

To generate this linear combination of the three frequency sources, a proposed algorithm is shown in the block diagram in Figure 2. Three modes are driven into resonance by three individual oscillator circuits. The output frequency of each oscillator is passed through a frequency multiplier and mixed with the other outputs. By choosing appropriate multiplication/division coefficients found by Equation (4), the final output frequency of the system should be independent of temperature to second order.

RESULTS

In this work, three resonant modes on a single DETF

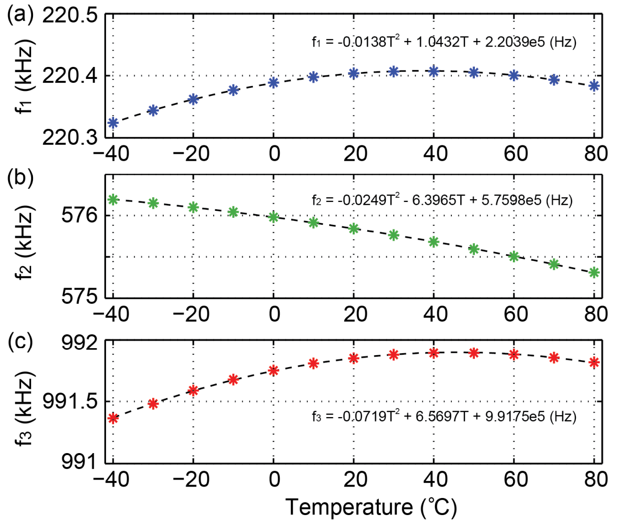

Figure 5: Quadratic fitting of the frequencies of the three resonant modes as a function of temperature. The star-shaped markers indicate the measured frequencies, while the black dashed lines show the fitted parabolic curves.

Table 1: Summary of fitted coefficients of the three resonant modes that describe the frequencies in the quadratic form: $f_i = \alpha_i T^2 + \beta_i T + f_{i,0}$, *where i is the mode number, T is temperature.*

Mode	α_i (Hz/°C^2)	β_i (Hz/°C)	$f_{i,0}$ (Hz)
1	-0.0138	1.0432	2.2039e5
2	-0.0249	-6.3965	5.7598e5
3	-0.0719	6.5697	9.9175e5

resonator are chosen (Figure 3). Two out-of-plane (OOP) modes (mode #1 and #2) are driven and sensed through a shared pair of top electrodes with two digital phase-lock-loops (PLLs). In-plane electrodes are used for the oscillation of in-plane (IP) mode (mode #3) with an analog oscillator circuit. Figure 3 shows the open-loop frequency responses of the three modes at room temperature and their mode shapes. The three resonant frequencies are at 220.4kHz, 575.8kHz and 991.9kHz, respectively. All of the three modes are oscillated in closed loops simultaneously, and the frequency of each mode is tracked.

As the device is fabricated in highly doped n-type single crystal silicon and aligned with <100> crystal orientation, the three resonant modes exhibit unique TCf characteristics, as shown in Figure 4. Each of the three temperature-frequency curves is fitted to a quadratic expression following the form of equation (1). The curve fits are shown in Figure 5. Table 1 summarizes the fitted coefficients for each mode. As discussed, to eliminate both first and second order temperature dependence of the output frequency, optimal coefficient A and B can be calculated by Equation (4). With the fitted data listed, A and B are calculated to be -0.0255 and -0.1836, respectively. This gives an output frequency of 23.61kHz with minimized temperature dependence.

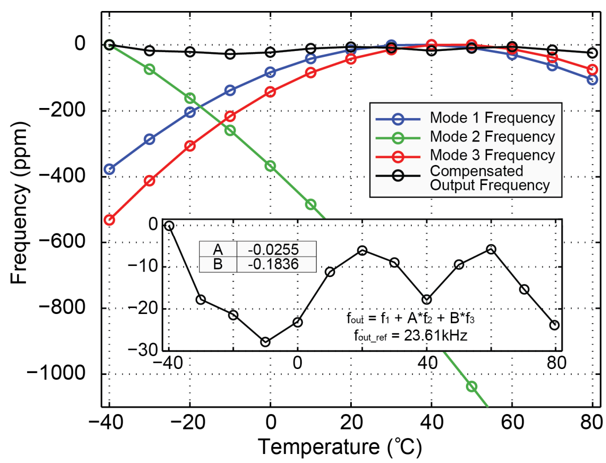

Figure 6: Compensated output frequency vs ambient temperature. ±14ppm residual temperature dependence is observed due to the frequency deviations of the three modes from true parabolic temperature dependence.

Based on the extracted coefficients, the expected output frequency is estimated and plotted in Figure 6 as a function of temperature. As shown, the temperature dependence of the output frequency is significantly reduced in comparison with the original frequencies of the three resonant modes. A residual frequency drift of ±14ppm over -40~80°C is shown, which indicates an improvement of ~15x over the first mode and ~55x over the second mode. Sources of the residual frequency shift include measurement error and any deviation from parabolic fitting of the three frequencies.

CONCLUSION

Demonstrated in this work is a novel temperature compensation method by frequency synthetization with a tri-mode operation scheme on a single silicon MEMS resonator. Three resonant modes present unique temperature dependence of frequency due to the heavy doping and crystal orientation. By carefully choosing the coefficients to form a linear combination of the frequencies of three resonant modes, a temperature insensitive output frequency can be generated. In this proof-of-concept work, we demonstrate a total frequency shift of ±14ppm over a large temperature range of -40~80°C, a total ~15x improvement. The proposed algorithm can be realized by using a fractional-N PLL as the frequency multiplier, in conjunction with a frequency mixer and various filters. In addition, the temperature dependence of the output frequency can be adapted to any quadratic form by simply modifying the values of the coefficients A and B.

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