

VERY HIGH FREQUENCY STABILITY OF SINGLE-CRYSTAL SILICON THERMAL-PIEZORESISTIVE RESONATORS WITH PHASE-LOCKED LOOP

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ABSTRACT

This paper reports on a single-crystal silicon (Si) thermal-piezoresistive resonator (TPR) achieving very high frequency stability in phase-locked loop (PLL) measurements. A pair of resonators operating in a balanced-bridge configuration is presented, with one device being driven at resonance and the other used to null the background response. The resonance frequency of the single TPR is collected over 40 hours with closed-loop tracking by PLL and yields Allan deviation $\sigma_A \approx 2.66$ ppb for an averaging time $\tau \approx 4.95$ seconds, which is the lowest reported value among all Si TPRs studied to date. This result is significant as it suggests that such TPRs can potentially achieve frequency stabilities comparable to, or better than, existing state-of-the-art resonators used in oscillator circuits, with significantly reduced external thermal control requirements and power demands.

KEYWORDS

MEMS resonator, thermal-piezoresistive resonator (TPR), frequency stability, Allan deviation.

INTRODUCTION

Thermal-piezoresistive resonators (TPRs) have recently been demonstrated as frequency-stable resonant microelectromechanical systems (MEMS). Among earlier TPRs, the piezoresistive MEMS heat engine was reported in 2011 [1]. There has been growing research to examine the effects of self-sustained oscillation (SSO) and thermal-piezoresistive feedback in these devices. To date, TPRs have been demonstrated for sensing [2–5] and signal amplification [6–8]. They are a new class of internally transduced resonant devices that can offer comparative performance benefits such as low motional resistance [9], high effective quality (Q_{eff}) factor [10], and reduced thermal control requirements, thanks to the thermal-piezoresistive internal feedback that is built-in. Previous works have reported single-crystal Si TPRs with good frequency stabilities while operating at their SSO thresholds [11,12]. However, there has not been much research on the frequency stability of a single-crystal Si TPR operating below the SSO threshold.

In this work, we report on investigating the frequency stability of a pair of TPRs operating in a balanced-bridge circuit, with a phase-locked loop (PLL) employed to track the frequency of one of the resonators. All measurements are performed under a vacuum of ~ 70 mTorr and with the TPR operating below the SSO threshold. We achieve an Allan deviation (σ_A) of approximately 2.66 ppb for an averaging time (τ) of 4.95s, compared to $\sigma_A \approx 40$ –90 ppb for $\tau \approx 0.02$ –1s reported in literature.

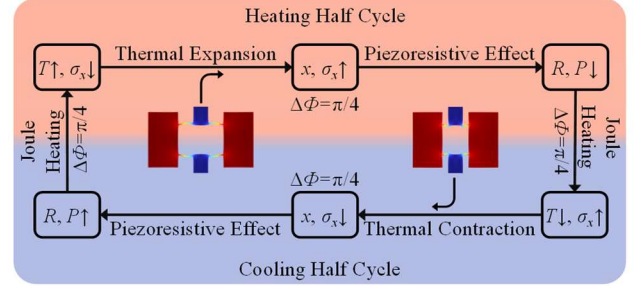


Figure 1: Thermal-piezoresistive feedback transduction block diagram describing how the TPR operates and illustrating the intrinsic internal feedback loop, depicting the changes in device temperature (T), actuator stress (σ_x), device displacement (x), actuator resistance (R), and actuator power (P), with their respective physical effect causing the changes in device parameters. Insets show maximum expansion (contraction) of the longitudinal mode shape when heating (cooling) occurs in the TPR.

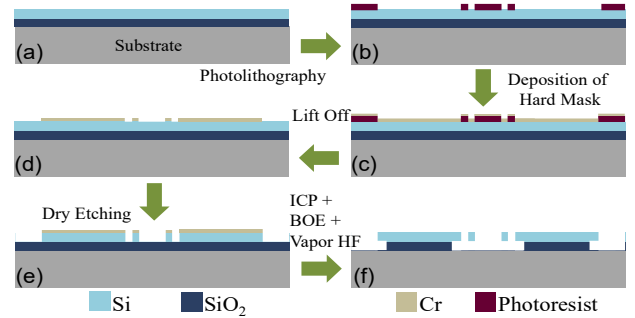


Figure 2: Microfabrication of the Si TPR via an SOI wafer based single-mask process for suspended resonators.

EXPERIMENTAL METHODS

The resonators have been fabricated along the $\langle 100 \rangle$ direction of Si crystal to maximize the negative longitudinal piezoresistive coefficient necessary for creating the thermal-piezoresistive feedback illustrated in Fig. 2a. It is comprised of four piezoresistive beams that act as thermal engines for the resonator when driven by both DC and AC (or radio-frequency, RF) currents. The piezoresistive beams are connected to an anchor (which also serves as a contact), and two identical suspended proof masses (Fig. 2b). In this work, we examine the potential impact of utilizing the TPR to generate an ultra-stable frequency source. We hypothesize that the intrinsic internal feedback offers enhanced Q_{eff} which could contribute to a higher frequency stability.

The TPRs are fabricated using an n-type doped Si-on-insulator (SOI) wafer with $N_d \approx 8 \times 10^{19}$ estimated doping concentration calculated from measurements. The wafer has $2\mu\text{m}$ thick Si and SiO_2 buried oxide (BOX) layers.

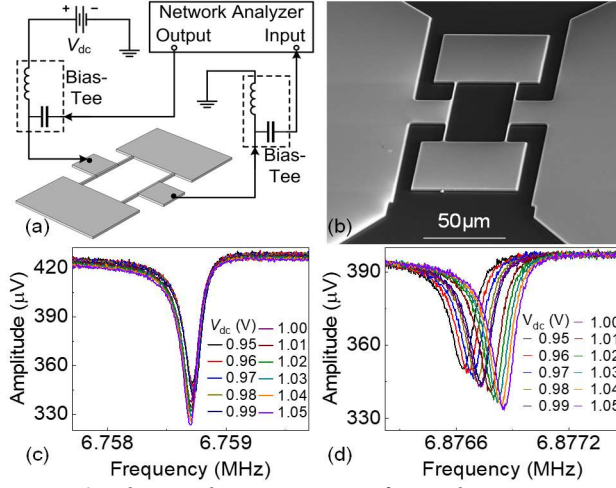


Figure 3: Electrical measurement of a single resonator and the measurement results. (a) Measurement circuit scheme for driving a single resonator and measuring its resonance response. (b) Scanning electron microscopy (SEM) image of the TPR with thickness $t=2\mu\text{m}$. (c) Measurement of resonance response for device A as V_{dc} is swept from 950mV to 1.05V. (d) Measurement of resonance response for device B as V_{dc} is swept from 950mV to 1.05V.

Photolithography and lift-off are performed to pattern a hard mask of chromium (Cr) onto the surface of the wafer, followed by a dry etch to pattern the Si device. Finally, the hard mask is removed, and an inductively coupled plasma (ICP) reactive ion etch (RIE) is used, in addition to buffered oxide etchant (BOE) and vaporized hydrogen fluoride (HF), to release the resonator from the BOX layer and allow it to be suspended (Fig. 2).

RESULTS & DISCUSSIONS

Experimental Results of Individual Resonators

We first characterize the individual TPRs using a network analyzer to determine which device has a more pronounced resonant response for our intended experiments. To characterize an individual TPR, we use the scheme in Fig. 3a to drive each device with both DC and RF power to their in-plane longitudinal mode (Fig. 3b). We then measure the resonance response of each device while the DC bias voltage (V_{dc}) is swept from 950mV to 1.05V and measure the corresponding shift in the resonance frequency (Fig. 3c and 3d). The applied voltage does not exceed 1.05V to prevent device failure. The TPR in Fig. 3c shows resonance frequency upshift as we increase V_{dc} from 950mV to 980mV, and resonance frequency downshift as V_{dc} increases above 980mV, showing a near zero voltage coefficient of frequency ($VCf \approx 0$) at $V_{dc}=980\text{mV}$. When the device is electrically driven, Joule heating of the actuators both raises their temperature and induces stress from thermal expansion. Consequently, the negative temperature coefficient of Young's modulus (TCE_Y) in Si softens the longitudinal stiffness which reduces the resonant frequency. With the increase in thermal stress due to the elevated temperature, it is believed that an effective stiffness in the thermal beams is increased, which subsequently raises the resonant frequency of the TPR. Future analyses will be performed on the device to identify the underlying cause of the increased effective stiffness

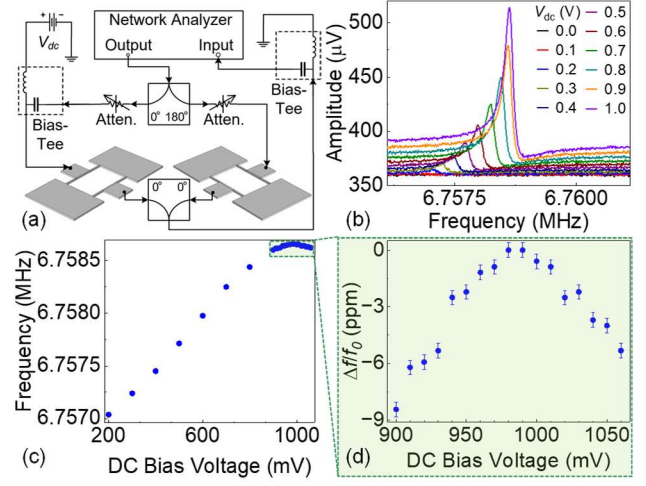


Figure 4: Electrical measurement scheme for a pair of resonators operating in a balanced-bridge circuit, along with measurement results. (a) Measurement circuit scheme for driving a single TPR (device in Fig. 3c) at resonance while nullifying the background by driving a second TPR 180° out of phase. (b) Frequency response of bridged circuit as V_{dc} is swept from 0mV to 1V. (c) Resonance shift obtained from the TPR as V_{dc} is swept from 0mV to 1.06V. (d) Zoomed-in plot of (c) from 900mV to 1.06V plotted in ppm, showing the region where $VCf=0$ for the TPR.

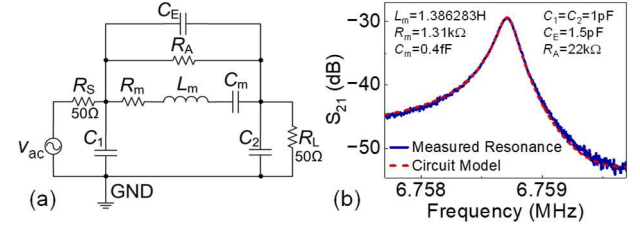


Figure 5: Equivalent circuit model and simulation results for a single resonator in a balanced-bridge configuration. (a) Equivalent circuit model for a single TPR without background, used for comparison to experimental results obtained from balanced-bridge configuration. (b) Comparison of results from equivalent circuit simulation and experiment (when $V_{dc}=980\text{mV}$), with the exact values for circuit elements that are used to generate the plotted resonance shown inside.

and subsequent resonant frequency increase. In our measurement, we achieve $VCf=0$ via balancing these two effects by carefully controlling V_{dc} . To prevent any resonant frequency instability induced by noise from the DC power supply, the device which shows a $VCf=0$ is chosen for future measurements.

Experimental Results of Balanced-Bridge Circuit

After we determine the individual device that will be used to perform further experiments, we connect both devices in a balanced-bridge circuit (Fig. 4a). This circuit drives device A with both DC and RF current while driving device B with an RF current 180° out of phase. By connecting the devices in this scheme, we nullify the background response in device A. We then characterize the resonator over a range of DC voltages (Fig. 4b). We find the highest resonance frequency of $f=6.759\text{MHz}$ for a corresponding DC bias voltage of $V_{dc}=980\text{mV}$ (Fig. 4c).

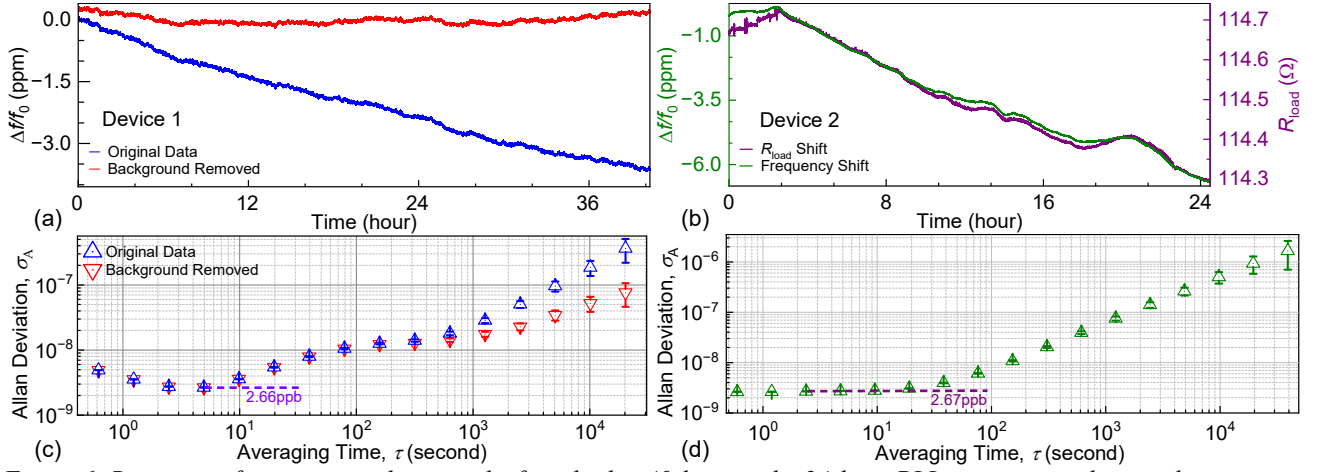


Figure 6: Resonance frequency tracking results from both a 40-hour and a 24-hour PLL operations, along with respective calculated σ_A results. (a) Measurement results from 40-hour PLL tracking resonance frequency of bridged resonator with (red) and without (blue) linear long-term frequency drift subtracted. (b) Measurement results from a 24-hour PLL with a constant DC bias current of 7.5mA delivered to a different resonator (green) while recording the total load resistance of the balanced-bridge circuit in Fig. 4a (purple). (c) σ_A versus τ calculated from 40-hour PLL data, showing a minimum σ_A of 2.66ppb for original data (blue) and a lower σ_A at longer τ values with the linear background subtracted (red). (d) σ_A versus τ for 24-hour PLL data, showing a nearly identical minimum σ_A of 2.67ppb at a τ smaller than in the previous result, as well as a long-term frequency stability that degrades at a faster rate than the previous measurement.

This characterization is performed to ensure that we are operating the TPR at the zero-slope point for VCf (Fig. 4d). Additionally, we employ the equivalent circuit model in Fig. 5a to extract circuit parameters by comparing the simulated curve obtained from the model to experimental results (Fig. 5b). We use these compared results to estimate $Q_{eff} \approx 41,000$ for the device connected in the balanced bridge circuit in Fig. 4a.

Frequency Stability for a TPR in a PLL

After device characterization, we replace the network analyzer in Fig. 4a with a lock-in amplifier to construct a PLL to track the resonance frequency for ~ 40 hours to check the stability of the response. After 40 hours of testing, the resonance frequency has drifted around -3.6ppm and shows a linear deviation over time (Fig. 6a). The observed frequency variation shows an apparent long-term frequency drift over the ~ 40 -hour measurement, which is hypothesized to be a result of a variation in the power delivered to the device. The power variation is thought to result from a change in the electrical resistance of the device (R_A in Fig. 6a). If the linear long-term frequency drift is removed, the resultant frequency fluctuation is only a few hundred ppb, exhibiting excellent stability performance. The background subtracted frequency shift data is a calculated result obtained by performing a linear fit on the frequency tracking data then subtracting the resultant fit from the original data.

To determine if the linear long-term frequency drift could be due to changes in electrical parameters, we run another 24-hour PLL with a constant current of 7.5mA supplied by a Keithley 2450 SMU and track the change in load resistance (R_{load}). A different TPR is used in this PLL, to determine if the results were unique to the previous resonator or not. We note that the change in the resistance and frequency of the TPR circuit are in alignment and show a similar linear background

response to that of the first pair of resonators that we measured (Fig. 6b). This result appears to confirm our hypothesis that the resistance of the device changes over the duration of the PLL, causing a linear long-term resonant frequency drift. We hypothesize that using an external feedback loop to supply constant DC power to the device could remove this linear background and produce a result similar to that seen in Fig. 6a. From the 40-hour frequency stability measurement, we obtain $\sigma_A \approx 2.66$ ppb for $\tau \approx 4.95$ s (Fig. 6c). The background subtracted PLL data shows better σ_A at larger τ values, and identical σ_A at smaller τ values when compared to the original data. The 24-hour PLL results show a marginally lower $\sigma_A \approx 2.67$ ppb for $\tau \approx 2.39$ s, and noticeably worse σ_A results for larger τ (Fig. 6d). Overall, we have achieved σ_A values approximately 15 to 35 times better than the reported values within the literature for similar devices operating at and below their SSO thresholds (Table 1).

Future Improvements to Device Stability

There are a few potential enhancements to our current measurement scheme that can be implemented to further improve the frequency stability of our resonator. As it has been previously discussed, using an external DC power supply feedback loop could decrease the

Table 1: Comparison of frequency stability measured from various state-of-the-art TPRs, showing frequency stability (σ_A) in this work being the best among all reported values in literature. *This reported work is for SSO operation, all others are below the SSO threshold.

σ_A (τ)	f_0 [MHz]	Device & Material	Ref.
2.66×10^{-9} ($\tau \approx 4.95$ s)	6.759	Si TPR	This Work
89.07×10^{-9} ($\tau \approx 1$ s)	0.9292	Si TPR	[3]
85×10^{-9} ($\tau \approx 0.8$ s)	5.1	Si TPR	[4]
$*40 \times 10^{-9}$ ($\tau \approx 0.02$ s)	0.9227	Si TPR	[12]

instability of our measurement by removing the linear long-term background frequency drift. The resonance frequency and Q_{eff} of TPRs have been shown to exhibit temperature hysteresis with reduced temperatures [13] and a steep reduction in resonance frequency and flattening of Q_{eff} at higher currents and temperatures [14]. Thus, controlling the temperature fluctuations of the environment could also lead to enhanced frequency stability and better σ_A results for the TPRs.

CONCLUSION

In summary, very high frequency stability of TPRs in balanced-bridge circuit configuration with PLL has been demonstrated. Allan deviation of $\sigma_A \approx 2.66$ ppb for an averaging time of $\tau \approx 4.95$ seconds has been achieved over a 40-hour PLL measurement *without external temperature control*. The lowest reported σ_A in this work is approximately 15 to 35 times better than values reported in literature for Si-based TPRs, showing a promising potential for Si TPR MEMS enabled resonant sensors and timing devices. The stability levels attained here may be further improved with the addition of on-chip temperature control or an external feedback loop that can supply the TPR with a constant DC power.

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