AN EFFECTIVE TEMPERATURE COMPENSATION ALGORITHM FOR CMOS-MEMS THERMAL-PIEZORESISTIVE OSCILLATORS WITH SUB PPM/ºC THERMAL STABILITY

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ABSTRACT

A real-time temperature compensation method using resistance control with two-point calibration, implemented in a CMOS-MEMS thermal-piezoresistive oscillator (TPO), has been demonstrated in this work. To enhance the thermal stability of the CMOS-MEMS TPO for future mass/aerosol sensing applications, a novel algorithm is proposed to attain a temperature coefficient of frequency (*TCF*) of only -0.5 ppm/ºC which is 66 times improvement over uncompensated case. The implemented TPO has no passive compensation as the structure is made of CMOS back end oxide and polysilicon to obtain a high quality factor (*Q*) of 2,000 in air. The heater resistance serves as ambient temperature sensor. As a result, the proposed method only requires measurement at two temperature points to modify the controlled resistance of the heater and is much more convenient than other low *TCF* methods utilizing look-up table (LUT) or polynomial equation fit.

INTRODUCTION

The 20th and 21st centuries have seen rapid industrialization and infrastructure growth, leading to densely populated urban areas. This has resulted in steady increase in pollution and has adversely affected the environment. The main concern now is the alarmingly high levels of particulate matters (PM) in major cities. These particles have adverse effect on human health, and smaller the particle the more severe they are in the long-term deterioration of health. $PM_{2.5}$ is known to cause cancer of lungs and general respiratory issues [1][2]. Need for a portable, convenient and low cost PM sensor is essential to guarantee hearty family life. Mass sensors are ideal candidate to meet this goal; however the current technology requires bulky and expensive facility. MEMS based sensors are omnipresent in consumer products due to their small form factor and ease of integration with electronic systems. Furthermore, MEMS based resonant mass sensors provide high sensitivity in addition to previously stated benefit of low cost, low power, and being compact [3]. Among MEMS resonant sensors, thermal-piezoresistive resonators (TPR) have seen increasing focus due to their high-*Q* in air [4] and self-oscillation [5]. However, self-oscillation is only feasible for materials with high piezoresistive coefficients (e.g., single crystal silicon) and still can be power hungry with very short lifetime and poor reliability. To address the abovementioned issues, CMOS-MEMS process allows us to integrate the MEMS and circuits to design a traditional MEMS oscillator. In such an approach, the back end of line (BEOL) materials, such as oxide and polysilicon, have low loss and the latter one can be used as micro heaters (actuators) and piezoresistive sensors [6].

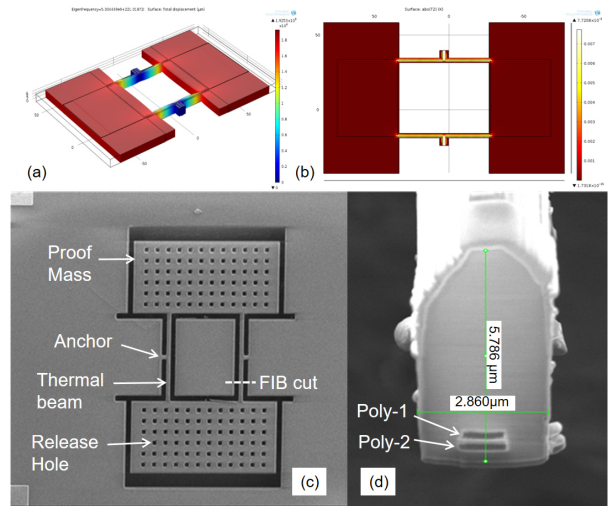

Figure 1: (a) Length extension mode shape at 5 MHz for II-BAR. (b) Temperature distribution under AC excitation with maximum temperature change of 7 mK. (c) SEM top view and (d) FIB cut of the thermal beam.

To understand the working principle of the proposed device, the $PM_{2.5}$ attaches to the resonator, thus causing a change in mass which corresponds to change in its resonance frequency. To accurately detect particle mass, the proof-mass of the resonator should have constant velocity profile and the resonance frequency should be fixed, i.e., insensitive to other environmental factors. Constant velocity can be achieved by selecting a suitable resonator vibration mode. Frequency stability is not only critical for communication and timing reference applications, but also essential for mass sensing. For example, a resonator with 20 Hz/pg sensitivity and *TCF* of 10 ppm/°C with resonance at 5 MHz would have a resolution of only 212 pg over commercial temperature range (85°C span). To achieve a mass sensing resolution of 10 pg with *TCF* of 10 ppm/°C would require the TPR to have mass sensitivity of 436 Hz/pg. Thus, in the absence of a temperature invariant TPR, a very high sensitivity mass sensor would be required to have sufficient resolution for fundamental science (high-resolution mass sensors for physical, chemical and biological areas) and industry applications [7]. The sensitivity can be increased by increasing the frequency or reducing the proof-mass size. Higher resonance frequency is power inefficient for the TPR while smaller proof-mass could be easily saturated. Hence, achieving a *TCF* of sub-ppm/°C is desirable.

In this work, we propose an active temperature compensation algorithm using the polysilicon embedded heater as temperature sensor with two-point calibration to overcome the frequency fluctuation caused by ambient temperature variation. This is verified using National Instrument's LabVIEW and a cryogenic vacuum probe station. Frequency stability of the entire setup was also measured to obtain an estimate of the best resolution for possible mass sensor implementation.

DESIGN AND WORKING PRINCIPLE

Thermal-Piezoresistive Resonator

An II-BAR resonator was adopted due to its length extension mode where the proof-masses of the resonator feature constant velocity, as shown in Figure 1(a). The TPR has a resonance frequency of around 5 MHz and it consists of BEOL silicon-oxide and polysilicon. In TSMC's 0.35 µm CMOS process, there are two polysilicon layers, i.e., Poly-1 and Poly-2. Poly-1 has low resistivity and is used as heater for low power operation while Poly-2 has high resistivity and acts as the piezoresistor. Temperature distribution under AC signal demonstrates the temperature gradient across the thermal beams of the TPR as can be seen in Figure 1(b). The two-poly process allows for separating driving and sensing resistors, which removes the resistive feedthrough observed in SOI TPR [6]. The symmetric II-BAR configuration allows utilization of a differential scheme for driving and sensing.

Fabrication process was same as [8], where first a metal wet etching was done on the received die from foundry. To open the probing pads, a dry SiO_2 etching was performed followed by dry silicon etching using xenon difluoride (XeF_2) gas to release the device. A scanning electron microscope (SEM) image of the released device is shown in Figure 1(c) along with the proof-masses with release holes and thermal beams. Cross-sectional cut of the thermal beam is visible in Figure 1(d) using a focused ion beam (FIB), indicating the Poly-1 heater and Poly-2 piezoresistor.

Temperature Compensation

In our previous work [8][9], we have used a constant resistance (constant-*R*) control method to maintain a fixed structural resistance, thus leading to a constant temperature to achieve reduced frequency variation. There is a significant improvement of *TCF* from an uncompensated case of about 33 ppm/°C to -8 ppm/°C. Typical oven control methods utilizing the same control scheme achieves almost 0.15 ppm/°C compensation [10]. The major limiting factor in realizing similar *TCF* is the inherent temperature gradient across the thermal beam. All oven control designs strive to be isothermal to have a very linear relation for heater resistance (R_H) versus ambient temperature (T_{amb}). In our case, the second-order temperature coefficient of resistance (TCR_2) for Poly-1 is negligible and hence R_H vs. T_{amb} is still linear but

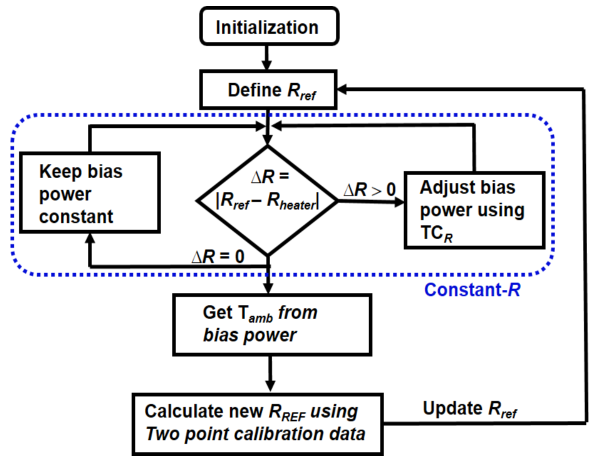

Figure 2: Flow chart of the proposed algorithm for real time temperature compensation by constant-R of the heater with linear correction factor for heater resistance using two-point calibration.

the second order effects of the temperature coefficient of elasticity (TCE_2) cannot be ignored and will cause a drift in frequency despite constant R_H. This frequency drift needs to be compensated to further improve the *TCF*. To demonstrate the improvement of thermal stability in this work, it is convenient to measure the frequency of an oscillator rather than a resonator. As a result, a lock-in amplifier with phase locked-loop (PLL) was utilized to implement the proposed thermal-piezoresistive oscillator (TPO).

ALGORITHM

To implement our idea, a flow chart representation of the proposed algorithm is depicted in Figure 2. The heater resistance needs to be initialized as process variation will cause deviation from its nominal value (R_{ref}). The method consists of two routines. The first routine is the traditional constant-*R* control. Bias power is adjusted if a change in resistance (ΔR) exceeds tolerance limit to reach the R_{ref} value. The second routine is executed once the first routine has reached a steady state. Ambient temperature can be easily estimated as R_H vs. T_{amb} is linear. Based on first routine, the bias power will also be a linear function of temperature. The

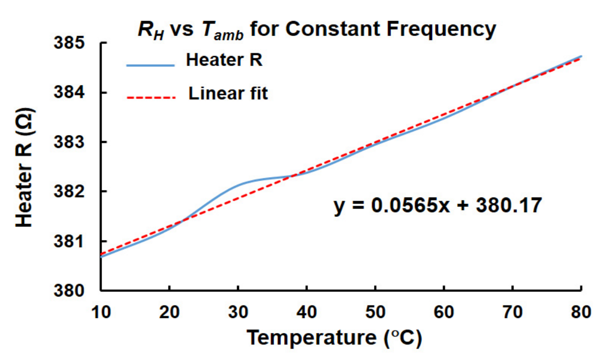

Figure 3: Heater resistance vs. ambient temperature for a constant frequency.

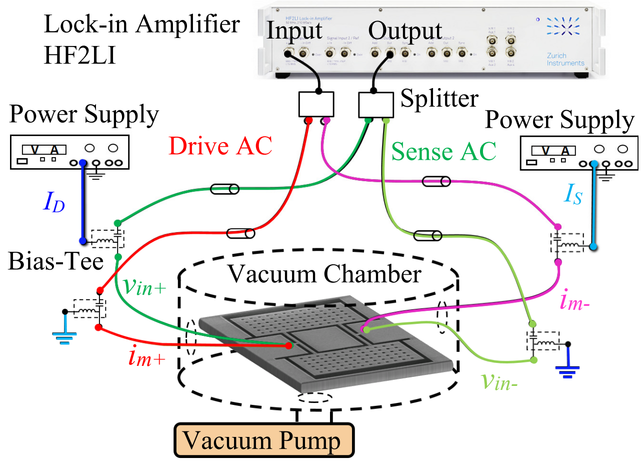

Figure 4: Measurement setup of the CMOS-MEMS TPO.

easiest way to compensate would be to directly monitor frequency, but this can only be reliably implemented using a look-up table (LUT) or would need a counter with a stable clock source. Alternatively, to characterize the behavior of the TPO, the bias power was adjusted to achieve constant frequency over entire working temperature range. Figure 3 shows that the heater resistance vs. ambient temperature for constant frequency has a linear relation and can be completely modeled using two-point calibration. This linear fit was used to calculate the heater resistance value to achieve zero frequency deviation at current ambient temperature. The R_{ref} value is updated and the process continues.

MEASUREMENT SETUP

The TPR is combined with a lock-in amplifier with PLL to create an oscillator. The TPO measurement setup along with DC and AC connection schematic is shown in Figure 4. Bias-Tees are used to supply both DC and AC to the TPR where Poly-1 heater has differential driving and Poly-2 is used for differential sensing. A DC bias current (I_D) is applied to Poly-1 for thermal drive and another DC current (I_S) for Poly-2 sensing. The TPR is placed in a vacuum chamber of the probe station. Output of the TPR is connected to the input port of the lock-in amplifier while its output is used to drive the TPR into sustained oscillation. Keithley source meter units (SMU) are used to provide DC bias. Output of the lock-in amplifier is also connected to Agilent frequency counter. LabVIEW interfaces with SMU, probe station temperature controller, and frequency counter to control and read the bias power, temperature, and output frequency respectively. Temperature is ramped at a rate of 3°C/min. This allows automated temperature compensation.

RESULTS AND DISCUSSION

Open loop response of the TPR is first characterized using a network analyzer. Figure 5(a) presents the magnitude and phase responses for a fully differential setup. The resonance frequency was 5.13677 MHz under a total bias power of 1 mW in vacuum with Q of 10,600 and the phase at resonance is almost 0°. The same device exhibits Q greater

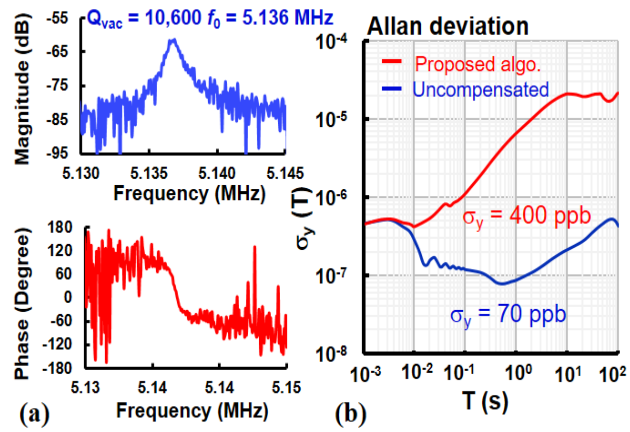

Figure 5: (a) Two port differential driving and differential sensing ($S_{D_{43}D_{21}}$) magnitude and phase plots. (b) Degradation of Allan deviation from 70 ppb for the uncompensated TPO to 400 ppb for the temperature compensated TPO.

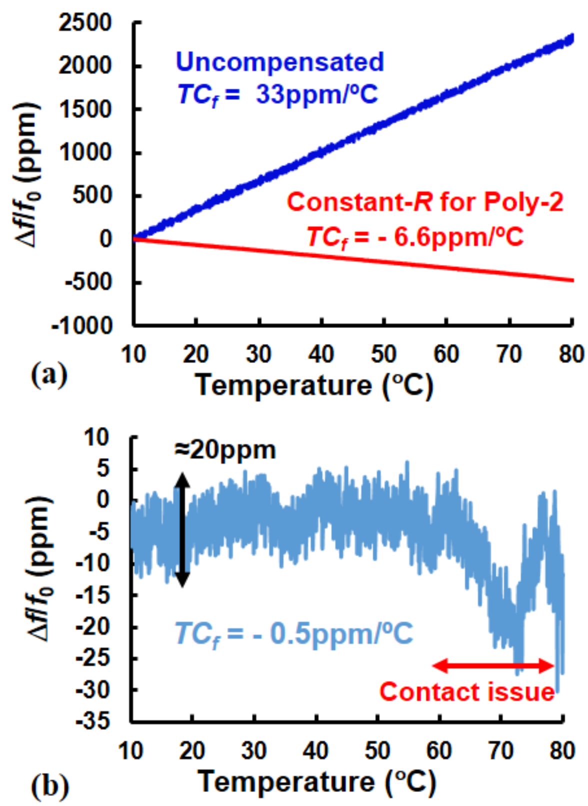

Figure 6: Frequency stability measurement for ambient temperature change from 10ºC to 80ºC. (a) TCF of the uncompensated TCO (blue) and the constant-R approach for Poly-2 sensing resistor (red). (b) TCF for two-point calibration of the constant-R control of Poly 1 heater resistor is -0.5 ppm/ºC; frequency variation of only 20 ppm is observed up to 60ºC and the dip is attributed to contact issue due to probe tips expansion above 60ºC.

than 2,000 in air with a total bias power of 2 mW.

As mentioned previously the TPR was connected to a lock-in amplifier with PLL to form a TPO. Frequency counter was used to analyze the frequency stability on an uncompensated TPO and was found to be 70 ppb as can be seen in Figure 5(b). This translates to mass sensor resolution on the order of few tens of femto-grams.

The uncompensated TPO has a *TCF* of 33 ppm/°C as determined from Figure 6(a), which would translate to a resolution of 600 pico-grams. This would limit its $PM_{2.5}$ detection capability. A constant-*R* control is used for Poly-2, where Poly-2's resistance was kept constant by varying the heater (Poly-1) bias. This results in a *TCF* of -6.6 ppm/°C, thus achieving a resolution of approximately 150 pico-grams. Using the proposed algorithm, the heater resistance is corrected based on ambient temperature reading using the two-point calibration. Figure 6(b) shows that *TCF* over 10°C to 80°C was found to be around -0.5 ppm/°C. This is an improvement of over one order compared to the previously reported value for CMOS-MEMS TPO [8]. A mass sensing resolution of 10 pico-grams was thus demonstrated. The sharp dip at 70°C is attributed to probe tip displacement due to thermal expansion. It is possible to obtain frequency variation of less than 10 ppm over the temperature range of 80°C. The drawback of the proposed compensation algorithm is the degradation of the frequency stability. The TPO with the proposed constant-*R* approach with two-point calibration has a minimum frequency deviation of 400 ppb which is almost 6 times more than that of the uncompensated case, as shown in Figure 5(b). Therefore, the best resolution possibly is 0.1 pico-grams.

Furthermore, the proposed scheme does not require additional power or area as it utilizes the heater resistor as the temperature sensor. The logic can be implemented as part of microcontroller of a System on Chip (SOC) or as an ASIC. The control loop's compensation speed is expected to be determined by the thermal response time of the TPR, which in this case is about 4 ms. Hence, the system has a low bandwidth requirement, i.e., potential for very low power ASIC. This method is easier to implement as it needs measurement at just two temperature points instead of the time consuming and expensive LUT.

CONCLUSION

A CMOS-MEMS TPO under a real-time constant-*R* temperature compensation algorithm with two-point calibration was demonstrated. Frequency variation due to inherent temperature gradient in TPR for a constant-*R* control was overcome by applying a correction to the constant-*R* based on T_{amb}. Temperature information is obtained from bias power as it is linearly related to T_{amb} for the heater. The proposed method achieved a *TCF* of -0.5 ppm/°C over a temperature range of 80°C. Thus, demonstrating an improvement of more than an order compared to previously reported value for a CMOS-MEMS TPR. This was achieved without need for additional power or area. The TPO can achieve a mass resolution of 10 pg with the implemented temperature compensation scheme and potentially lead to sub-pico grams in future. Further analysis is required, namely effect of process variation on the relationship of R_{ref} vs. T_{amb} for constant frequency to simplify the algorithm logic (lower power) or higher-order compensation like in the case of bandgap voltage reference to achieve near zero *TCF*.

ACKNOWLEDGEMENTS

The research was sponsored by Ministry of Science and Technology (MOST 105-2221-E-007-136-MY3).

REFERENCES

[1] P. A. Solomon, *et al.*, "Macroscopic to microscopic scales of particle dosimetry: from source to fate in the body," *Air Qual. Atmos. Health*, vol. 5, pp. 169-187, 2012.

[2] D. Hu and J. Jiang, "PM2.5 pollution and risk for lung cancer: A rising issue in China," *J. Environmental Protection*, vol. 5, pp. 731-738, 2014.

[3] C. Hadji, *et al.*, "Hollow MEMS mass sensors for real-time particles weighing and sizing from a few 10 nm to the µm scale," *Proc. IEEE MEMS, 2015*, pp. 180-183.

[4] S. J. Hyeong and O. Brand, "High-*Q*-factor in-plane-mode resonant microsensor platform for gaseous/liquid environment," *J. of Microelectromechanical Systems,* vol. 17, pp. 483-493, 2008.

[5] X. Guo, Y.-B. Yi, and S. Pourkamali, "Thermal-piezoresistive resonators and self-sustained oscillators for gas recognition and pressure sensing," *J. IEEE Sensors*, vol. 13, no. 8, pp. 2863-2872, 2013.

[6] J.-H. Chang, *et al.*, "Performance evaluation of CMOS-MEMS thermal-piezoresistive resonators in ambient pressure for sensor application," *Proc. IEEE Int. Frequency Control Symposium, 2015*, pp. 202-204.

[7] E.-C. Chang, M.-H. Li, C.-C. Chen, C.-H. Chin, and S.-S. Li, "Real-time mass sensing and dynamic impact monitoring of printed pico-liter droplets realized by a thermal-piezoresistive self-sustained oscillator," *Proc. IEEE MEMS, 2016*, pp. 1078-1081.

[8] C.-S. Li, *et al.*, "A low voltage CMOS-MicroElectroMechanical Systems thermal-piezoresistive resonator with $Q > 10,000$," *IEEE Electron Device Letters*, vol. 36, no. 2, pp. 192-194, Feb. 2015.

[9] C.-C. Chen, *et al.*, "Enhancement of temperature stability via constant-structural-resistance control for MEMS resonators," *Proc. IEEE MEMS, 2013*, pp. 765-768.

[10] C.-S. Liu, *et al.*, "Temperature compensated MEMS oscillator using structural resistance based temperature sensing," *Proc. IEEE SENSORS, 2015*, pp. 1-4.

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