ON-MEMS-CHIP COMPACT TEMPERATURE SENSOR FOR LARGE-VOLUME, LOW-COST SENSOR CALIBRATION

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ABSTRACT

The work introduces a MEMS temperature sensor for use in the same module of other sensors, to provide optimal measurements for their thermal calibration/compensation purposes. The sensor, made of 25-µm-thick, lowly-doped, epitaxial polysilicon, relies on a multi-mode resonator, where the frequency ratio is used to extract relative temperature changes without the need of an external absolute time reference. Measurements across the [5-85]°C range validate the predictions of the frequency behavior, enabling to estimate ±50 $\mathrm{mK_{rms}}$ resolution at 4-Hz data rate.

KEYWORDS

MEMS, multi-mode resonators, temperature sensors, temperature coefficient of frequency.

INTRODUCTION

The performance of several MEMS sensors is determined by stability over temperature T [1]. Though efforts are put to understand underlying phenomena [2], the behavior vs temperature remains perturbed by n^{th}-order effects (e.g. parasitics drift and package stress, among the others) which are hard to model and predict. A need for calibration vs T is thus often mandatory. Several times the T sensor is aboard the integrated circuit or the printed circuit board (PCB): this means that, under spatial or temporal temperature gradients, the T estimate is inaccurate due to steady-state temperature offsets between MEMS and circuit, and/or due to their different thermal constant, yielding sub-optimal compensation. A solution could be a local T measurement, close to the MEMS sensor.

In this context, it is known that the natural frequency of MEMS resonators changes with T in a well repeatable manner, especially at low doping values [3]. However, not always a sensor has a self-sustained mode in operation (e.g. accelerometers); sometimes the sensor has one resonant mode (e.g. the gyroscope drive); even if more modes are forced (e.g. in FM gyroscope), they have nominally identical temperature coefficients of frequency (TCf). Can one infer relative temperature changes $\Delta T = T - T_0$ from a single mode with frequency $f(T)$, properly calibrated at a reference temperature T_0? Given the equation:

$$f(T) = f(T_0)(1 + \alpha \Delta T) \quad \Rightarrow \quad \Delta T = \frac{f(T) - f(T_0)}{\alpha f(T_0)} \tag{1}$$

where α is the linear TCf, the answer apparently seems: *yes*. However, to measure a frequency, one needs a frequency/time reference, which is itself an oscillator, which may itself drift. As this typically occurs, the issue is not solved. The key-point would be to avoid the need for an absolute, accurate frequency/time reference. This work proposes a T sensor based on a multi-mode resonator fabricated in a large-volume MEMS technology [4], compatible with low-cost applications and free of the need for an absolute time/frequency reference.

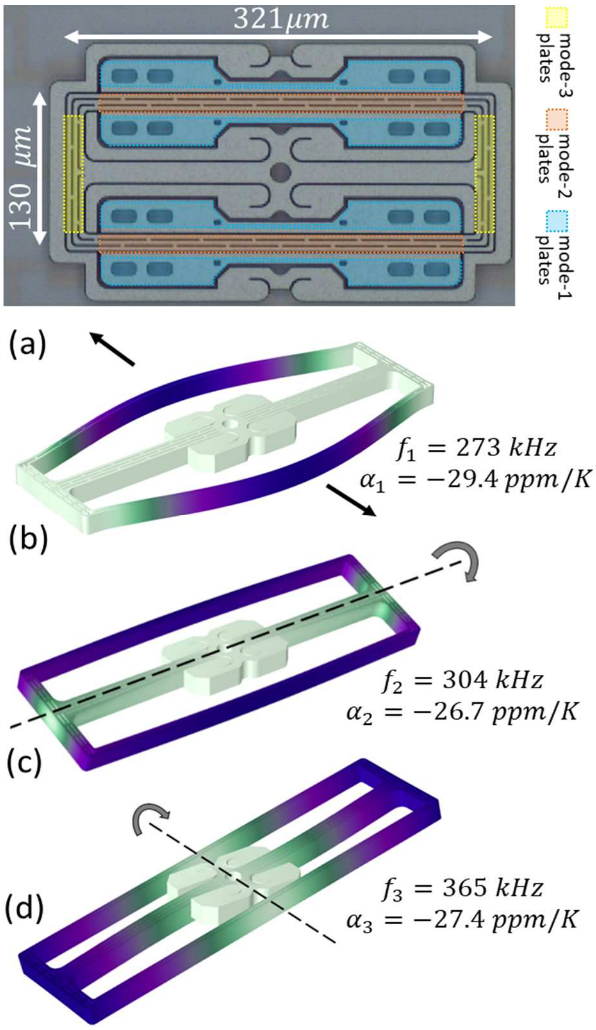

Figure 1: scanning electron microscope image of a 3-mode resonator (a) with the electrodes to drive and sense the three modes highlighted in colors. The modal shapes, frequencies and predicted TCfs are shown in plots (b-d).

THEORY OF OPERATION

The sensor is based on the simultaneous oscillation of both flexural and torsional modes in a MEMS structure. The T dependence of the density and of the two elastic constants describing the constitutive laws of low-doped polysilicon, assumed as linear isotropic elastic material, can be derived from [5]: a different TCf can be then expected for different modes, as long as they are characterized by different distributions of flexural, shear

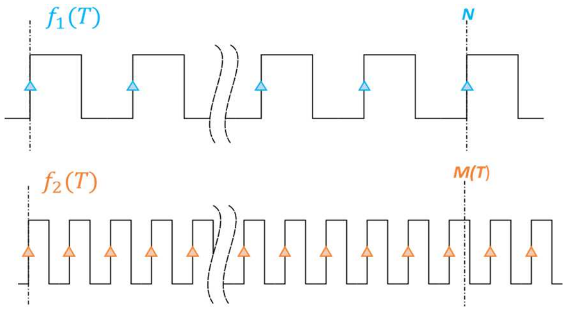

Figure 2: scheme of the temperature measurement method of this work: with two modes having different TCf, the number of periods M of the fast mode f₂(T) that fits in a prescribed number N of periods of the slow mode f₁(T) is a function of T and is used as a sensing method independent of an absolute time/frequency reference.

and torsional strains. If a difference can be observed in the temperature dependence of different modes of a single MEMS resonator, then the simultaneous actuation of at least two of its modes would enable the implementation of the self-referenced temperature sensor as described below.

The reference structure for the experiments is the one reported in Fig. 1a. The device, fabricated by STMicroelectronics using the ThELMA process [6], is anchored only in the center, and its main resonant mode is the flexural one whose mode shape is represented in Fig. 1b, based on the anti-phase bending of two silicon beams. The nominal resonance frequency is about 273 kHz. The other two resonant modes that can be exploited for the sensor are the torsional ones represented in Fig. 1c-d. These modes show a resonance frequency of about 304 kHz and 365 kHz, respectively. The device is actuated via parallel plates: Fig. 1a reports the electrodes arrangement for each mode. While the flexural mode can be actuated and sensed differentially, via the four electrodes highlighted in blue, the other two are inherently single-ended due to the arrangement of the electrodes.

Fig. 1 also reports the expected temperature dependence of each resonance frequency as calculated by FEM analysis: the average value of the TCf α is in the order of -30 ppm/K, as expected for silicon, however the coefficients of the three modes show a difference of a few ppm in their absolute value, corresponding to ~ 6%. Such small difference is enough to enable the sensor realization.

Its basic working principle is represented in Fig. 2 using the waveforms associated to just two modes, labeled $f_1(T)$ and $f_2(T)$. The idea is to adopt a counter to measure the number of cycles of both modes that fall within a given observation interval. However, the duration of such interval is not fixed as a value in seconds by an absolute reference; rather, it is given by a number N of cycles of the slowest of the two modes, i.e., $f_1(T)$ in the example. Thus, as temperature changes, the number of cycles N remains constant, but both the length of the measurement window and the number of cycles M of the second mode that fall within such frame change according to temperature. The two frequencies are expressed as:

$$\begin{aligned} f_1(T) &= f_1(T_0)(1+\alpha_1\Delta T) \\ f_2(T) &= f_2(T_0)(1+\alpha_2\Delta T) \end{aligned} \tag{2}$$

where $T_0 = 25$ °C is a reference temperature chosen for the initial frequency calibration, α_1 and α_2 are the temperature coefficients, and $\Delta T = T - T_0$ is the deviation of T from the reference temperature. The temperature variation can be measured by taking the ratio of the frequencies:

$$R(T) = \frac{f_2(T)}{f_1(T)} \tag{3}$$

and evaluating its variation with respect to the reference temperature, i.e., $R(T) - R(T_0)$, resulting in the theoretical formula:

$$\Delta T = \left(\frac{R(T_0)}{R(T)}(\alpha_2 - \alpha_1) - \alpha_1\right)^{-1}. \tag{4}$$

An estimate of such exact quantity can be inferred from direct measurement of the number of cycles, minus a quantization error. Expressing the frequency ratio as a function of the number of counted cycles, the temperature estimate is written as:

$$\widehat{\Delta T} = \left(\frac{N}{M(T)-M(T_0)} R(T_0)(\alpha_2 - \alpha_1) - \alpha_1\right)^{-1}. \tag{5}$$

For small temperature-induced frequency variations, i.e., if $\alpha_1\Delta T \ll 1$, the expression can be simplified, resulting in:

$$\widehat{\Delta T} \approx \frac{\Delta M(T)}{N}\frac{f_1(T_0)}{f_2(T_0)}\frac{1}{\alpha_2-\alpha_1} \tag{6}$$

where $\Delta M(T) = M(T) - M(T_0)$.

In (6) the value of N is chosen accounting for the bandwidth of the measured temperature variations. Given the desired output data rate (ODR) of the sensor, the value of N is chosen according to:

$$N < \frac{f_1(T_{max})}{\text{ODR}} \tag{7}$$

where $T_{max} = 85$ °C is the maximum temperature that corresponds to the minimum value of f_1.

The number of cycles $M(T)$ is measured in real-time. Thus, there are four parameters that require an initial calibration, namely the nominal resonance frequencies at T_0, and the temperature coefficients of the two modes. The value of $M(T_0)$ derives from N and the nominal frequencies. As such, a printed circuit board (PCB) based system was developed to both characterize these parameters, as well as to sustain the simultaneous oscillation of two modes and thus to implement the sensor.

EXPERIMENTAL SETUP

Fig. 3a shows the circuit architecture adopted to keep each of the two modes in self-sustained oscillation. The MEMS displacement is sensed via a charge amplifier (CA) followed by gain stages that raise the output voltage to the level of ~ 1 V. A phase-shifter (90D) adjusts the phase-lag of the loop transfer function to 0° to meet the oscillation condition. A variable-gain amplifier (VGA) adjusts the gain of the loop transfer function according to the output of an automatic gain control (AGC) circuit to keep the

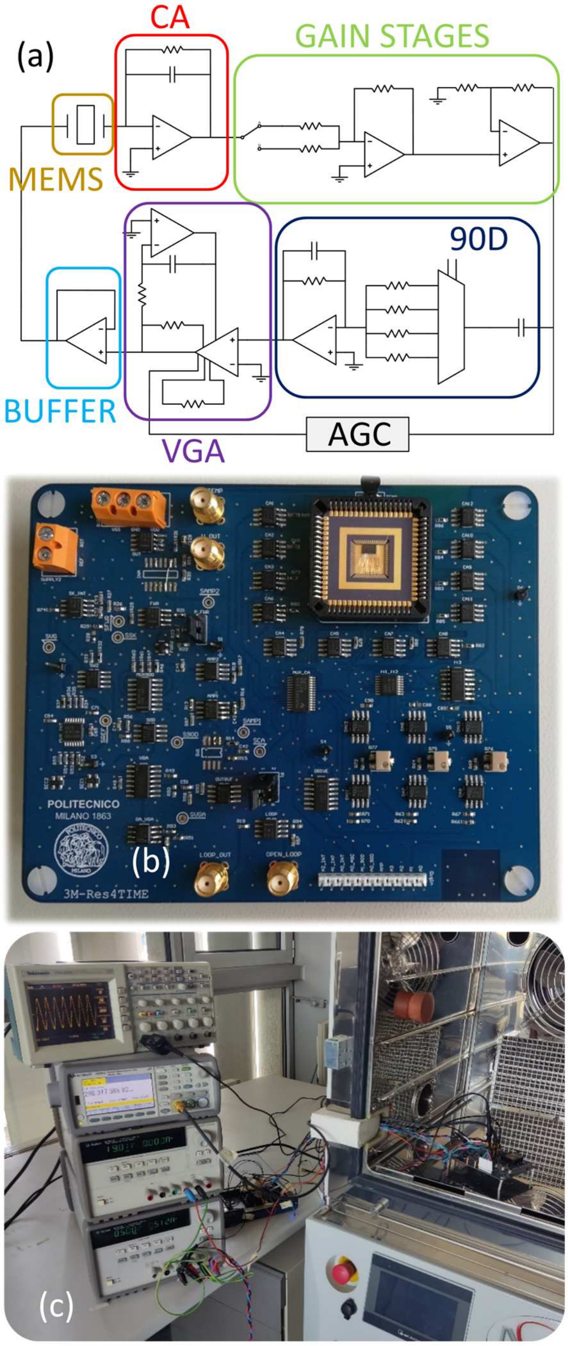

Figure 3: scheme of the oscillators (a) to sustain the modes. In (b-c) the board and climatic chamber setup are shown.

maximum displacement limited to about 200 nm, set using an external voltage reference. Finally, a buffer stage drives the MEMS actuators.

A switch is placed before the actuators to allow both open- and closed-loop operation. The former is used for preliminary characterization of the frequencies and temperature coefficients, while the latter is used for the sensor operation. The prototype PCB is shown in Fig. 3b.

Fig. 3c shows the whole setup, comprising the DC voltage generators for the ±5 V power supply, the rotor bias of about 20 V, and the AGC reference voltage, a frequency counter (Keysight 53230A), an oscilloscope and the climatic chamber to perform temperature tests.

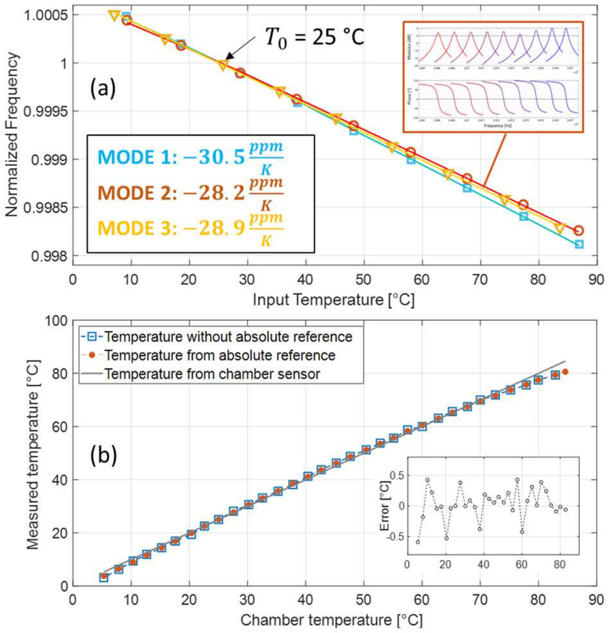

Figure 4: validation of TCf predictions through peak measurements vs T (a): results on the 3 modes show TCf trends in line with custom code predictions. Closed-loop operation (b) matches the use of an absolute reference (Keysight 53230A) within quantization (see the inset).

OPEN-LOOP CALIBRATION

Open-loop characterization was performed by sweeping the temperature from 85 °C to 5 °C with 10 °C steps and acquiring for each set-point the transfer function of the MEMS device on a frequency range centered on the resonance frequency. From such data, both the resonance frequency $f(T_0)$ at the reference temperature and the TCf can be extracted.

Fig. 4a shows the obtained TCf for the three modes. The inset shows a sample set of transfer function measurements, both magnitude and phase, used to extract the frequency data. Results well validate predictions, apart from an offset observed on all the modes: TCfs are all slightly larger than prediction, by 1.1 ppm for the flexural mode, and by 1.5 ppm for both the torsional ones. These results were repeatably obtained on eight different sets of resonators, belonging to two different MEMS dies.

CLOSED-LOOP OPERATION

Based on the results discussed in the previous section, Fig. 4b compares T measurements with the proposed method against the use of an absolute reference, i.e., the frequency counter which is kept outside the climatic chamber. The loop was closed for two modes, f_1 and f_2, corresponding to Fig. 1b and 1c, adopting two copies of the circuit of Fig. 3a. The nominal resonance frequencies for the device under test (DUT) are 276 kHz and 296 kHz, respectively.

The counter measures the oscillation frequency of both modes, and temperature is computed according to (4) – thus exploiting an absolute reference. The counter is also used to count the number of cycles of both modes, measuring over a gating time which varies as a function of temperature to keep the count N for the reference mode f_1 constant –

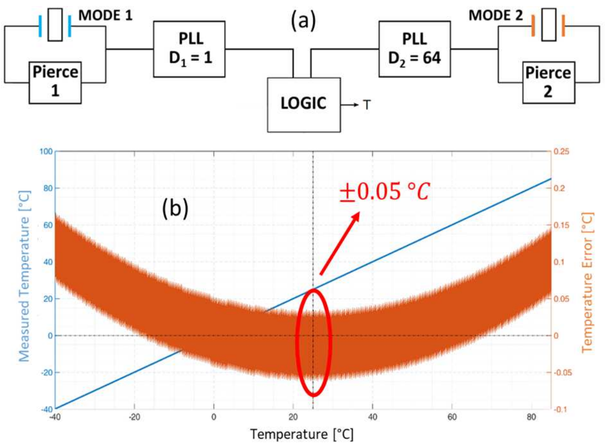

Figure 5: system-level scheme to reduce quantization error, while holding similar frequencies between modes. Pierce oscillators followed by PLLs with different DIV factor (a) yield ±50 mK quantization (b). A logic block implements the digital calculation of the ΔT equation in the text.

thus avoiding the absolute reference. Temperature is swept from 85 °C to 5 °C in 2.5 °C steps. The temperature calculation is then performed offline by a custom MATLAB code.

Measurement accuracy is dominated by quantization error, whose experimental value is shown in the inset of Fig. 4b, within about ±0.5 °C. The value chosen for N is $68 \cdot 10^4$, which enables a 0.4-Hz ODR. From a theoretical standpoint, the quantization error corresponds to the rounding error in counting M: the maximum value of such error thus corresponds to missing an entire period of f_2. Thus, it can be shown that the error improves by either increasing the observation interval, so the number of cycles N (which trades-off with the ODR); or increasing the ratio of frequencies R. The latter is the only viable solution to attain an acceptable ODR, i.e., in the order of a few Hz.

SYSTEM ARCHITECTURE

Attaining largely different frequencies, however, would require significantly different resonator topologies, inducing circuital differences which may be a source of mismatches and drifts. Therefore, it is preferred to keep a moderate frequency split between modes, use identical (well matched) oscillators, and further use a phase-locked-loop (PLL) after each oscillator with division moduli such to attain an additional frequency multiplication for mode f_2 (Fig. 5a). With this strategy, adopting two PLLs with division factors $D_1 = 1$ (buffer) and $D_2 = 64$ on f_1 and f_2 respectively, raising $f_{2,PLL}$ to 18.94 MHz, the quantization error drops below ±0.05 °C at a 4-Hz ODR, i.e., $N = 68 \cdot 10^3$, as shown by system-level simulation. Fig. 5b illustrates the overall temperature estimation error (orange curve). The quadratic dependence is related to the simplification introduced in equation (6) and can be eliminated by using the exact formula in equation (5), reducing the theoretical error down to ±0.05 °C due to quantization only. This is an acceptable value as it lies below the noise introduced by low-power Pierce oscillators.

CONCLUSION

This paper demonstrated the implementation of a temperature sensor based on the temperature-induced resonance frequency variations of multi-mode MEMS resonators. The sensor exploits the different temperature coefficients of two structural modes, enabling a self-referenced temperature measurement that does not rely on using a calibrated timing reference to readout the temperature-induced frequency variations. Results based on direct counting of the oscillators outputs shows that a 0.4-Hz ODR can be obtained with an accuracy of about ±0.5 °C. Increasing by a factor 64 the frequency of the “slave” mode using an integer-N PLL and performing counting on such upscaled reference should theoretically enable a 4-Hz ODR with a measurement accuracy within ±0.05 °C. Future work will focus on implementing the remaining parts of the system, namely the PLLs and a custom logic to perform temperature calculation, in order to implement a sensor with fully-digital output.

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