Temperature Sensing for MEMS Sensors: A Review, and Chances for the Frequency-Control Community

(*Invited paper*)

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***Summary*—With an increasing demand of higher and higher performance for several microelectromechanical system (MEMS) based sensors, accurate temperature calibration and real-time compensation become a key enabling factor. Approaches to temperature (T) sensing operated directly on the MEMS die have inherent advantages over T-sensing implemented on the integrated or board level electronics. This work provides a review of temperature sensing approaches, with a special focus on those implemented through resonant operation of microstructures, providing the latest results for MEMS-based T sensors.**

Keywords—temperature sensors; MEMS; frequency control; multi-mode resonator; polysilicon process.

I. Introduction

Several MEMS-based sensors rely on vacuum-sealed, high-quality factor resonators. It is the case of amplitude-modulated gyroscopes [1] and of frequency modulated gyroscopes and accelerometers [2-3]. Several foreseen future applications of such systems, even for consumer-grade, mass-market devices, require increased stability, which, in turn, implies improved performance over the temperature range in terms of offset and scale-factor drift. Though several efforts were put to minimize at the origin the sources of drift, by changing the working principle or the process, some aspects are not in the designers' hands (e.g. system soldering on the final board, and corresponding deformation of package under temperature). As a consequence, to bring consumer-grade sensors to the next generation of performance, their calibration under temperature and following real-time compensation is required. This process is however expensive if carried out for every single part, and inaccurate as long as temperature estimate is erroneous.

State-of-the art systems including T compensation rely on a assembly of wire-bonded MEMS and integrated circuit (IC), or on a ceramic carrier hosting a MEMS, soldered on a printed circuit board (PCB). In both cases, MEMS+IC or MEMS+PCB, the T sensor is located on the electronic system, and can be thus mm to cm away from the actual MEMS substrate.

The consequence is that, in presence of spatial temperature gradients (e.g. generated by a constant heat source, like an electronic block with large dissipation), or in presence of temporal gradients (e.g. due to a heat source switching on/off, or due to a change of the environmental temperature and different thermal transients of the MEMS substrate and the T sensor), the T estimate, and the corresponding correction, may be inaccurate with respect to the calibration phase.

As a consequence, temperature sensors integrated on the MEMS chip have been proposed since a few years. While relying on non-PTAT (proportional to absolute temperature) references, which may represent a disadvantage and require accurate calibration, they carry the intrinsic advantage of measuring directly the temperature of the MEMS substrate, providing an optimal estimate of the sensor operating condition. The paper reviews possible approaches to T-sensing at MEMS-die level, and presents most recent results about a technique compatible with consumer-grade MEMS fabrication processes.

II. Review of MEMS-Based Temperature Sensors

While several times such MEMS-integrated temperature sensing solutions were developed to stabilize oscillators, using a T sensor and a T-compensation machine, all concepts can be easily readapted to temperature sensing only. In [4], the group from Georgia Tech exploited the large temperature dependence of the electrical resistance (TCR) of a Lamè mode resonator. In details, a specific operating point at high temperature was chosen where the TCR is large (> 1400 ppm/K), and the system was ovenized at that temperature by controlling the difference between the active resistance of the resonator and a stable reference resistor. Due to resistor-based sensing, even excluding the ovenization process, the system consumption was however as large as 70 mW.

Resonant based temperature sensing solutions, relying on a single-mode resonator, were proposed e.g. by KAUST [5]. Here the goal was to exploit the large TCf of clamped-clamped beam resonators, where the Young's modulus related TCf of silicon (-30 ppm/K) is largely overcome by pre-stress-related effects, leading to a TCf as large as 325 ppm/K. The technique repeatability is thus poor, and, additionally, still depends on the presence of an absolute time reference as mentioned above.

Solutions based on dual-resonator or multi-mode resonator architectures, with different TCf for the modes, were developed in various works by Stanford and SiTime (e.g. ref. [6]). Here the idea is to exploit the large difference in TCf that can be achieved by a different crystallographic orientation and doping of resonators integrated in the same die. Void of the need for an absolute time reference, this strategy relies on a frequency-ratio engine to determine the actual temperature of the MEMS die. No disadvantage can be envisioned for this solution (and best performance in terms of oscillator stabilization were indeed shown), except for the need of a specific process, which is more expensive than consumer-grade MEMS processes relying on epitaxial polysilicon instead of monocrystalline Si.

A solution that matches the requirements of consumer-grade processes was developed at METU [7]: here, temperature sensing is based on two identical double-ended tuning-fork resonators which are differently stressed in presence of temperature variations due to the presence of a strain amplifying beam for one of the resonators. As for the previous solution, the sensor does not need an absolute time reference, and a frequency-ratio engine can be used to extract temperature. The area taken up by the structure is relatively large, due to the two resonators and the amplifying lever, resulting in more than 1 mm^2, which is 4 times the area of a consumer-grade 1-axis accelerometer, thus incompatible with small-footprint solution.

III. Recent Results

Most recent works on the topic rely instead on a single structure, developed in a consumer-grade process, whose footprint is as small as 0.1 mm^2, where two modes are exploited [8], and whose resonances (around 250 kHz) are compatible with low-power (few mW) consumption [9]. The structure is shown as a reference in Fig. 1. The inherent disadvantage of this approach is that the obtainable TCf difference is small, causing either a poor temperature sensing resolution, or a low output-data rate (ODR), as the frequency-ratio engine needs to cumulate a significant difference in the number of cycles of the two resonators to provide an accurate T estimate. However, the newly introduced concept is to exploit a PLL multiplication of one of the frequencies, leading to the system shown in Fig. 2a. In this way, even a small TCf difference, can be exploited to provide accurate T estimates at reasonable data rate. As an example, Fig. 2b shows a 0.1-K resolution at 4-Hz ODR, which is compatible with most of inertial sensing applications. The high repeatability of the technology guarantees the possibility of family calibration and compensation (i.e. only a few parts are tested, e.g. 100 to 1000, and data are valid for a large family, e.g. a 10000-sensor wafer). This concept paves the way to the integration of T-sensing systems in the package of 3- or 6-axis inertial measurement units, to bring low-cost, consumer-grade sensors to the next generation of required performance, by enabling accurate compensation of offset and scale-factor drifts.

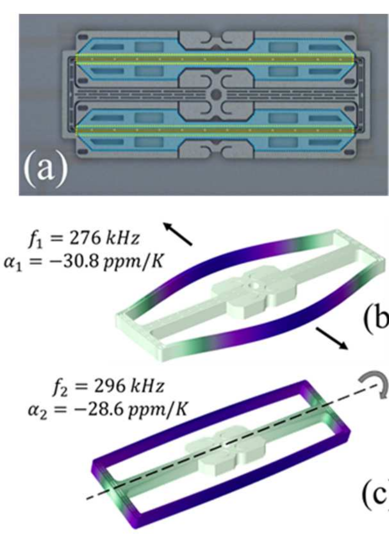

Fig. 1. Top view (a) of the dual-mode resonator, where an in-plane (b) and an out-of-plane (c) mode with slighlty different TCf (about -30 ppm/K and -28 ppm/K, respectively) can be simultaneously sustained.

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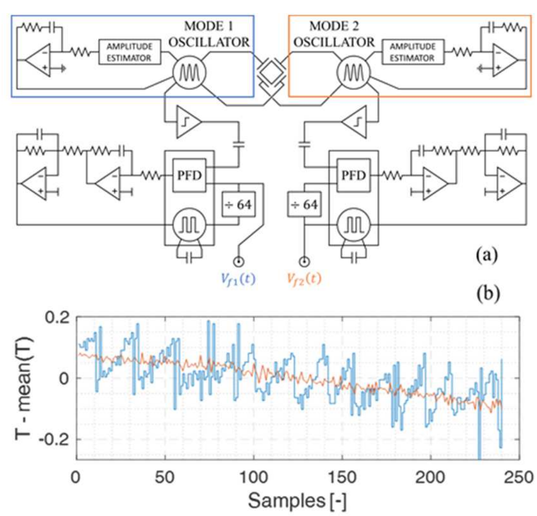

Fig. 2. Developed electronic system (a), exploting PLLs for frequency multiplication and improvement of the frequency-ratio engine accuracy. Results in (b) demonstrate 100-mK accuracy (the slow drift is an actual drift of temperature within the chamber).