# MONOLITHIC CMOS-MEMS OSCILLATORS WITH MICRO-DEGREE TEMPERATURE RESOLUTION IN AIR CONDITIONS

*J. Verd[1*], M. Sansa[2], A. Uranga[3], C. Pey[3], G. Abadal[3], F. Perez-Murano [2], and N. Barniol[3]*
[1]Electronic System Group, Universitat de les Illes Balears, Palma de Mallorca, 07122, SPAIN
[2]Institut de Microelectrònica de Barcelona, CNM-CSIC, Bellaterra (Barcelona), 08193, SPAIN
[3]Department of Electronic Engineering, Universitat Autònoma de Barcelona, Bellaterra, 08193, SPAIN

## ABSTRACT

This paper reports the thermal characterization of MEMS resonator-based oscillators fabricated using a conventional 0.35-µm CMOS process. The MEMS resonators are sub-micrometer scale metal beams which resonance frequency is highly dependent on temperature (up to -2055 ppm/ºC). Thanks to the monolithic integration of the oscillator electronics, the oscillator frequency stability is better than 1 ppm allowing temperature resolutions up to 0.00019ºC for 0.1 s averaging time, which is at least one order of magnitude better than the best previously reported.

## KEYWORDS

CMOS-MEMS, Microresonators, Digital temperature sensors.

## INTRODUCTION

The resonant frequency of MEMS resonators fabricated with CMOS technology shows a strongly dependence with temperature. The group of Prof. T.W. Kenny at Stanford University has taken advantage of this effect and recently has reported a CMOS-compatible MEMS temperature sensor with milli-degree resolution stating that is better than the best CMOS temperature sensors available [1]. It is a novel dual-resonator design which provides a temperature-dependent signal and a reference for measuring the signal.

In this paper we report the temperature characterization of metal beam resonators (i.e. clamped-free and clamped-clamped structures) which are the frequency-determining element of an oscillator circuit monolithically integrated in a commercial CMOS process. Due to the high temperature coefficient of frequency (TCf) that shows these resonators (in particular the CC-beam structure), a temperature resolution as low as 190 micro-degrees is demonstrated. In this case, to perform the measurement of the frequency shift due to temperature change an additional signal reference for on-chip/off-chip counting is needed. In any case, the relaxed specifications in terms of accuracy for this counter (around 10 Hz) allow the use of all-CMOS digital oscillators as reference clock (i.e. ring oscillators). In this sense, the presented devices can be used as on-chip temperature sensors as well as general-purpose temperature sensors with resolutions at least one order of magnitude better than reported in [1].

## DESIGN AND FABRICATION

The MEMS resonators are fabricated using the top metal layer of a commercial 0.35-µm CMOS technology as structural layer and post-CMOS processed using a simple mask-less wet-etching that allows an easy monolithic integration with CMOS circuitry [2].

In particular, two types of metal beam resonators have been fabricated; a cantilever resonator 10 µm long, 600 nm wide and 850 nm thick (Fig. 1b) with a resonance frequency of 6 MHz; and a clamped-clamped beam (CC-beam) resonator 18µm long, 600 nm wide and 850 nm thick (Fig. 1c) with a resonance frequency of 14MHz (CC-beam).

The resonators are electrostatically self-excited by means of an integrated oscillator circuit with a modified Pierce oscillator topology (Fig. 1a). This circuit has been full-custom designed enabling on-chip measurement of the resonance frequency of these sub-micrometer scale resonant structures. These devices have been used in previous works as mass sensors featuring both ultra-high mass resolution (~ag) and high spatial resolution (<100nm) [3].

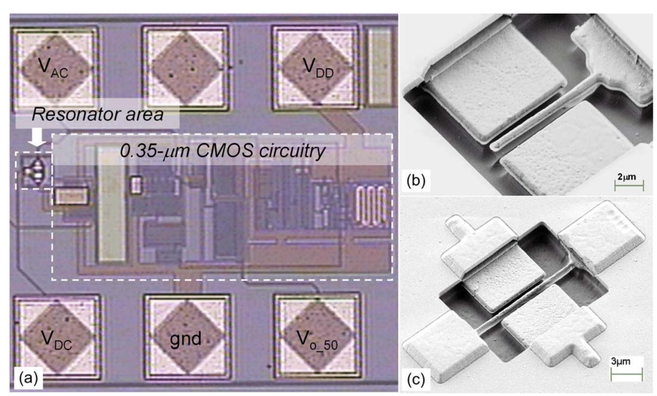


*Figure 1: (a) Optical image of the monolithic oscillator circuit based on a MEMS resonator. SEM images of a metal cantilever resonator (b) and a metal clamped-clamped beam resonator (c).*

## EXPERIMENTAL RESULTS

The two types of CMOS-MEMS oscillators addressed in this work have been experimentally characterized as temperature sensors. All the presented results have been obtained at ambient pressure.

### Temperature Sensitivity

The frequency of these metal CMOS-MEMS oscillators has been measured at different temperatures using the climate chamber SE-1000L (Thermotron) working at constant relative humidity of 15%. The measured TCf has been found to be -204 ppm/ºC for the cantilever resonator, while the CC-beam resonator exhibits a TCf as high as -2055 ppm/ºC which is one order of magnitude higher than reported in [1] that uses a dual-resonator. Both oscillators present also a very high linearity, as shown in Fig. 2, indicating that are also good candidates as temperature sensors.

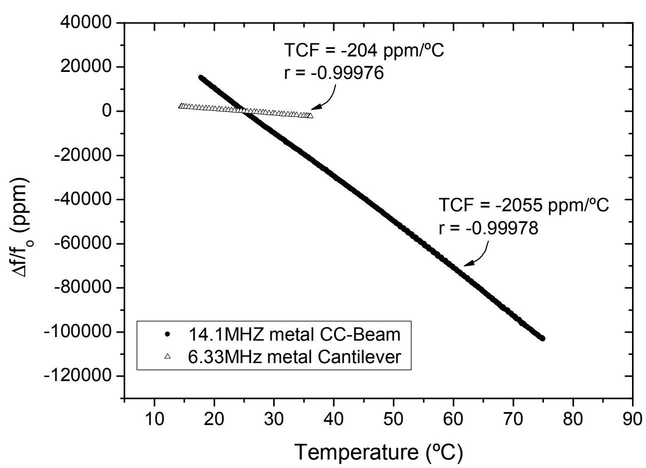


*Figure 2: Temperature dependence for the cantilever and CC-beam resonators.*

### Sensor Resolution

The temperature resolution of these monolithic sensors depends on the stability of the oscillator frequency output. The Allan deviation $\sigma_y$ [4] has been used to calculate the stability of the frequency measurements. The oscillator frequency has been measured using a programmable digital counter (HP 53131A) taking 100 samples for different integration (or averaging) times.

For the cantilever oscillator a minimum value of $\sigma_y$ = 0.54 ppm (equivalent to a frequency fluctuation of 3.4 Hz) is obtained for a 1 s averaging time (Fig. 3). This value combined with the cantilever temperature sensitivity gives a temperature resolution of 2.6 milli-degrees that is similar than reported in [1].

On the other hand, the CC-beam oscillator presents a $\sigma_y$ = 0.39 ppm (equivalent to a frequency fluctuation of 5.5 Hz) for a 100 ms averaging time (Fig. 4). This value is similar than that obtained for the cantilever structure, but its higher TCf results in a temperature resolution as low as 190 micro-degrees being at least one order of magnitude better than reported in [1].

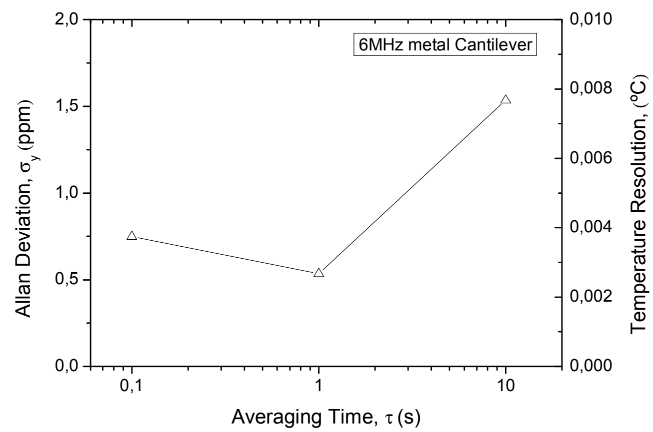


*Figure 3: Allan deviation as a function of averaging time and the corresponding temperature resolution of the cantilever resonator (air conditions).*

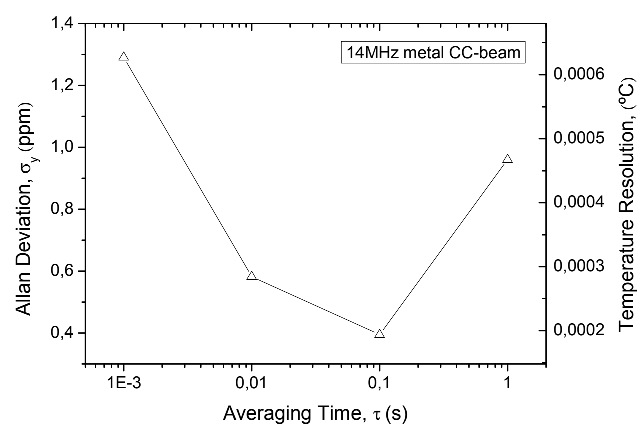


*Figure 4: Allan deviation as a function of averaging time and the corresponding temperature resolution of the clamped-clamped beam resonator (air conditions).*

### Long-term stability

Measurements of the frequency stability have also been performed for an interval time over 3 hours in order to observe the long-term stability of the sensors. The measurements have been performed into the climate chamber at constant temperature of 25ºC and relative humidity of 30%. An averaging time of 1 s has been chosen.

In Fig. 5, we can appreciate the fluctuation of the cantilever oscillator frequency ($f_o$ = 6.33 MHz) during the long-term measurements. The maximum variation observed was around 60 ppm which is corresponding with a temperature fluctuation of 0.12ºC.

In the case of the CC-beam oscillator (Fig. 6), the measured maximum frequency fluctuation was around 250 ppm ($f_o$ = 14.05 MHz) which is corresponding with a temperature fluctuation of 0.29ºC.

Taking into account that the climate chamber used may introduce temperature drift up to 1ºC, the results obtained are in agree with the expected. In this sense, the resolution of the MEMS sensors is below the stability of the measurement climate chamber and a higher performance unit would be used to improve the temperature stability during the measurements.

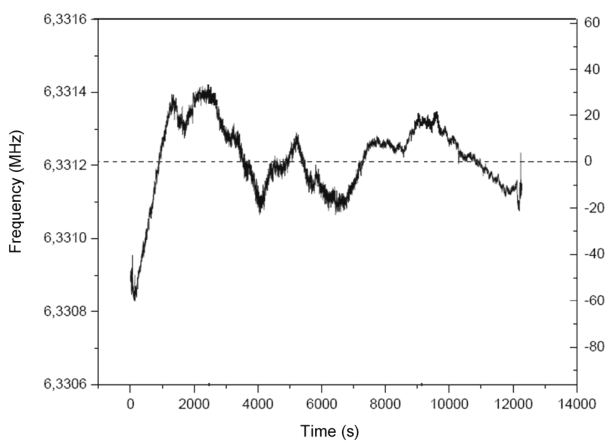


*Figure 5: Time-history plot of the cantilever oscillator frequency for an interval time over 3 hours.*

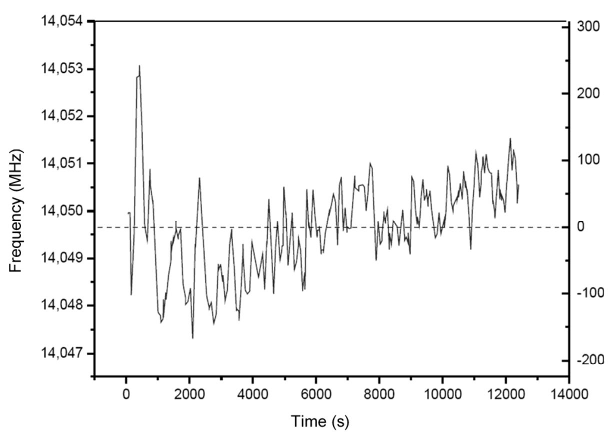


*Figure 6: Time-history plot of the CC-beam oscillator frequency for an interval time over 3 hours.*

## CONCLUSIONS

The results presented in this paper, and summarized in Table 1, indicate that metal MEMS-based temperature sensors can be developed using a commercial CMOS technology with a very simple and low cost fabrication process that allows the monolithic integration of CMOS circuitry.

Micro-degree temperature resolution has been achieved in air conditions. In this sense, ultrasensitive general-purpose digital temperature sensors can be fabricated using this approach without the need for an expensive encapsulated with vacuum sealing.

High temperature resolution is achieved mainly due to the high TCf that exhibits the metal CC-beam structure. An accuracy of only around 25 Hz on the oscillator frequency measurement is needed to obtain sub-millidegree resolution. In this sense, all-CMOS oscillators (i.e. ring oscillators) acting as reference clock of digital counters may be used to perform on-chip temperature measurements with ultrahigh resolution.

With these considerations, these metals oscillators can be used for on-chip temperature compensation, minimizing any spatial and temporal thermal lag, of other types of CMOS-MEMS resonators (i.e. MEMS reference oscillators, inertial sensors) specifically designed to experiment lower TCf values.

*Table 1. Allan deviation and temperature resolution (air conditions)*

| Metal resonator | Parameters | | | |
|---|---|---|---|---|
| | $f_o$ (MHz) | TCf (ppm/ºC) | $\sigma_y$ (ppm) | Resolution (ºC) |
| Cantilever | 6.33 | -204 | 0.54 | 0.0026 |
| CC-Beam | 14.05 | -2055 | 0.39 | 0.00019 |

## ACKNOWLEDGEMENTS


This work was partially funded by Spanish government under project MEMSPORT (TEC2006-03698/MIC). Applus+ corp. is acknowledged for some of the experiments on thermal characterization.


## REFERENCES


[1] C.M. Jha, G. Bahl, R. Melamud, S.A. Chandorkar, M.A. Hopcroft, B. Kim, M. Agarwal, J. Salvia, H. Mehta, and T.W. Kenny, "CMOS-Compatible dual-resonator MEMS temperature sensor with milli-degree accuracy", in Digest Tech. Papers Transducers'07 Conference, Lyon, June 10-14, 2007, pp. 229-232.

[2] J. Verd, A. Uranga, J. Teva, J.L. Lopez, F. Torres, J. Esteve, G. Abadal, F. Perez-Murano, and N. Barniol, “Integrated CMOS-MEMS with on-chip readout electronics for high-frequency applications“, IEEE Electron Device Letters, vol. 27 (6), pp. 495-497, 2006.
[3] J. Arcamone, M. Sansa, J. Verd, A. Uranga, G. Abadal, N. Barniol, M. van den Boogaart, J. Brugger, F. Perez-Murano, “Nanomechanical mass sensor for spatially resolved ultrasensitive monitoring of deposition rates in stencil lithography“, Small, in press.
[4] D. Allan, H. Hellwig, P. Kartaschoff, J. Vanier, J. Vig, G.M.R. Winkler and N.F. Yannoni, “Standard Terminology for Fundamental Frequency and Time Metrology”, in Frequency Control Symposium, 1988., Proceedings of the 42nd Annual, 1-3 Jun, 1988, pp. 419-425.

## CONTACT

* J.Verd, tel: +34-971-259569; jaume.verd@uib.es