Passive temperature-compensation of MEM resonators

X. Rottenberg [1], R. Jansen[1], S. Stoffels[1,2], J. De Coster[1], W. De Raedt [1] and H. A. C. Tilmans[1]

[1] IMEC v.z.w., Division MCP, Kapeldreef 75, B3001 Leuven, Belgium
xrottenb@imec.be

[2] K.U.Leuven, ESAT, Kasteelpark Arenberg 10, B3001 Leuven, Belgium

ABSTRACT

MEM-resonators are recognized key components for future sensing, wireless and communications applications. Si-based resonators have gained special interest since they offer the perspective to replace bulky quartz resonators on-chip, maintaining high Q-factor and reaching high frequencies. In various applications, e.g., time-reference, the temperature (T-) stability is of paramount importance. We propose a novel passive compensation of the T-drift of electrostatically-driven MEM-resonators. Key in our implementation is the T-driven modulation of the transduction gap that, controlled by design, can fully balance the T-drift due to the intrinsic material properties of the resonator. The further selection of the optimum bias working point allows compensating for potential processing inaccuracies. We apply this idea to bulk-mode bar resonators and derive a condition for full T-stabilisation.

Keywords: MEM resonator, temperature-stability, passive compensation, timing-reference, oscillator

1 INTRODUCTION

MEM-resonators are recognized as key components for future sensing, wireless and communications applications [1]-[3]. With their demonstrated high-Q, high-level of integration, small size and low cost, these components promise to achieve high detection sensitivity, even cheaper and more compact handsets with even longer battery life. Silicon-based resonators have gained special interest since they offer the perspective to replace bulky quartz resonators on-chip, *i.e.* above CMOS, maintaining high Q-factor and reaching high frequencies, all of this based on relatively standard processing techniques.

In various applications, *e.g.*, timing-reference, the temperature stability is of paramount importance. Typically, the intrinsic temperature dependence of the resonance frequency, f_{res}, is dominated by *ET*, the temperature coefficient of Young's modulus (*E*). For Si-based MEM resonators this temperature dependence is much larger than for quartz crystal resonators, and too large to allow the passive implementation of these resonators in high-end applications over wide temperature ranges, *e.g.*, -40°C to 85°C.

To circumvent this problem, two main approaches have been proposed in the literature:

1) Coating the resonator with positive *ET* materials, *e.g.*, SiOx, allows lowering the *ET* of the effective material composing the resonator, improving its overall temperature-stability [3][4]. This passive approach increases the processing complexity and costs, is often not effective to fully compensate the temperature-drift and can significantly degrade other resonator characteristics, e.g., its Q-factor.
2) Implementing an active control loop, composed of a thermometer and a heater, around the resonator allows limiting its temperature-excursion, thus its apparent temperature-drift, at the expense of increased design and process complexity as well as increased power consumption [5].

In this paper, we propose a novel passive compensation of the T-drift of electrostatically-driven MEM-resonators that extends the concepts presented in [6]. Key in our implementation is the temperature-driven modulation of the electrostatic transduction gap that, controlled by design, can fully balance the temperature-drift due to the intrinsic material properties of the resonator. The further selection of the optimum bias working point allows compensating for potential processing inaccuracies. We apply this idea to bulk-mode bar resonators and derive a closed form formula for the full temperature-stabilisation, working point and material selection.

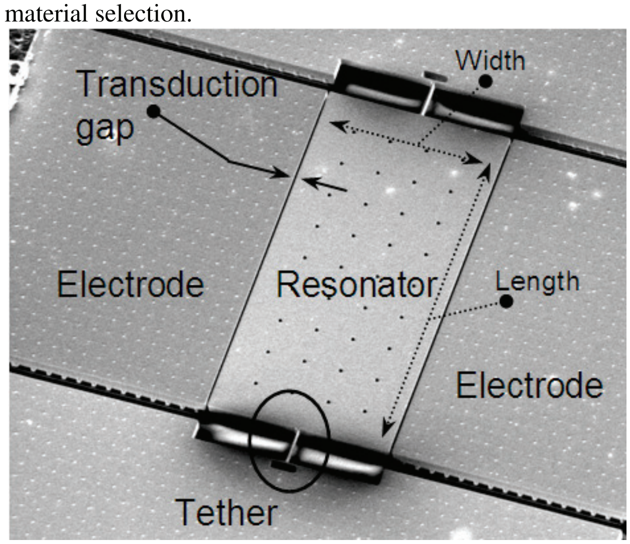

Figure 1 SEM photograph of a 50x100µm bar resonator [2]

2 BASIC MODEL AND T-DEPENDENCE

Figure 1 and Figure 2 present a typical MEM bar resonator. It consists of a free-standing parallelepipedic bar typically made of silicon. The resonator is anchored to the substrate through two tethers placed on opposite sides. Its two remaining opposite sides are further neighboured by two fixed electrodes that provide for electrostatic excitation and detection through two thin transduction gaps, *d*.

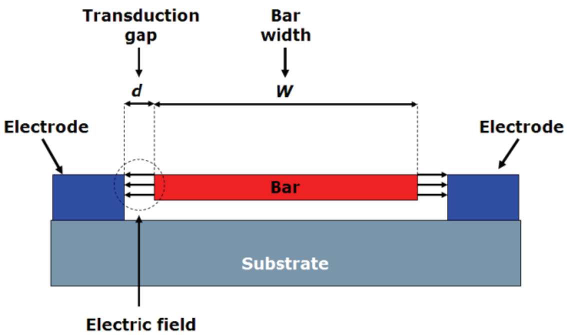

Figure 2 Cross section of the bar resonator from Figure 1

Such a bar resonator is typically used in its so-called longitudinal extensional mode where both transduction gaps shrink/expand in phase. Figure 3 sketches the equivalent electrical model of a bar in the vicinity of its extensional resonance frequency. The intrinsic bar model consists of a simple *RLC* resonant network in the mechanical domain coupled to the electrical domain through input and output transformers. These account for the electrostatic transduction taking place across the gaps defining input and output capacitors *C_coupl_in/out*. Additional parasitic capacitive and resistive components are depicted for completion.

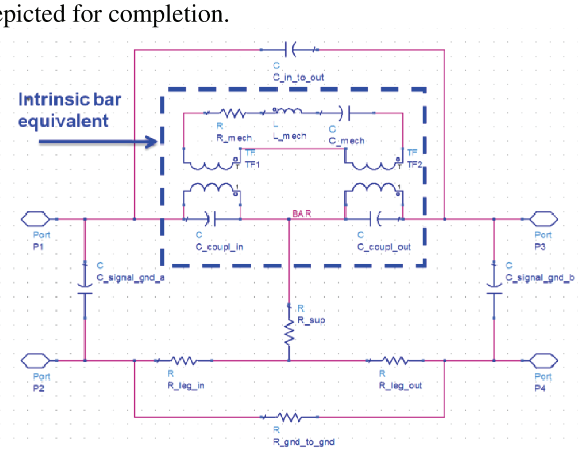

Figure 3 ADS schematic of the bar resonator from Figure 1

Neglecting Poisson's ratio ν, the intrinsic or natural resonance frequency f_{res} is given by (1) where W, E and ρ are respectively the width, Young's modulus and density of the bar. This simple equation expresses that, given the acoustic velocity of longitudinal waves in the bar material is given by (2), the bar width equals half a wavelength at f_{res}.

$$f_{res} \cong \frac{1}{2W}\sqrt{\frac{E}{\rho}} \tag{1}$$

$$v_{long} \cong \sqrt{\frac{E}{\rho}} \tag{2}$$

The temperature drift of the natural frequency of the bar resonator is obtained by expressing in (1) the temperature dependences on the one hand of W and ρ and on the other hand of E, respectively as functions of the *CTE* of the bar and its *ET*. For typical materials, *e.g.*, silicon, ET_{bar} dominates CTE_{bar} and in first approximation defines the temperature drift of the natural frequency. As shown in Figure 4, the temperature drift is almost linear with a slope close-to $ET_{bar}/2$.

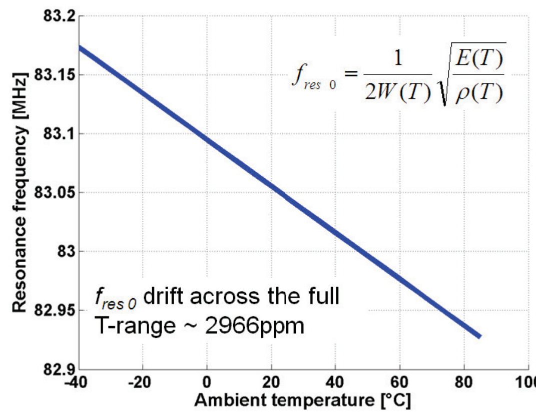

Figure 4 Temperature-dependence of the natural frequency of the bar resonator from Figure 1 produced in silicon with, at 25°C, W_{25}=50µm, E_{Si_25}=160GPa, ρ_{Si_25}=2320kg/m³, CTE_{Si}=2.6ppm/°C and ET_{Si}=-50ppm/°C

3 EXTENDED V- AND T-DEPENDENCES

MEM resonators require DC-biasing for their linear operation. This DC-offset introduces a parasitic electrostatic spring softening that result in a shift of f_{res} expressed by (3) for $V \ll V_{PI}$. The pull-in voltage V_{PI}, given by (4), is the modal pull-in voltage, *i.e.* the static voltage leading to a mode-collapse. The constant α was computed by Nathanson et al. [7] in a lumped approximation to be close-to 8, while the distributed developments by Tilmans [8] produce an analogous α_T close-to 6.5.

$$f = \frac{1}{2W}\sqrt{\frac{E}{\rho}\left[1 - \frac{\alpha}{27}\left(\frac{V}{V_{PI}}\right)^2\right]} \tag{3}$$

$$V_{PI} = \sqrt{\frac{16}{27}\frac{Ed^3}{\varepsilon_0 W}} \tag{4}$$

Figure 5 and Figure 6 demonstrate the effect of this voltage-dependence respectively on the isotherm characteristic of a MEM-resonator and on its temperature-dependence considering V_{PI} fixed.

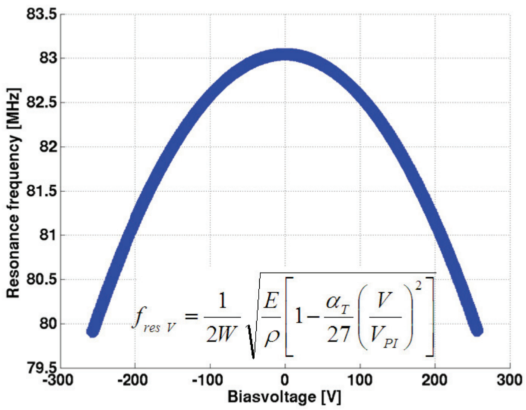

Figure 5 Voltage-dependence of the natural resonance frequency of the bar resonator from Figure 4 with nominal transduction gap d=100nm

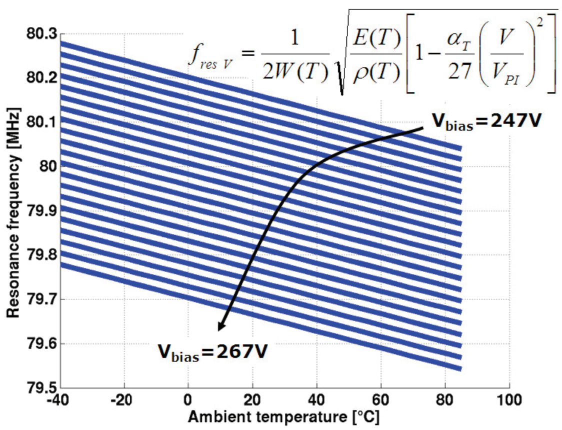

Figure 6 Temperature-dependence of the natural resonance frequency of the DC-biased bar resonator from Figure 5 neglecting the temperature-dependence of V_{PI}

The previous simulations neglect the temperature-dependence of V_{PI}. In practice, the temperature impacts the pull-in voltage through not only the characteristics of the bar resonator, i.e. material properties and geometry, but also through the transduction gap d. This gap can either increase or decrease with increasing temperatures, depending on the balance between the substrate CTE and the bar CTE as shown in Figure 7 assuming d<<<W.

It is striking to note that, while the previous temperature dependence of f_{res} was defined by ET_{bar}, a fixed material characteristic, the novel DC-bias term in (3) can be tuned by design or by selecting the working point, i.e. the DC bias voltage, and can be chosen positive or negative through an appropriate combination of resonator and substrate materials. This allows considering the passive compensation of the temperature-dependence of bar-resonators.

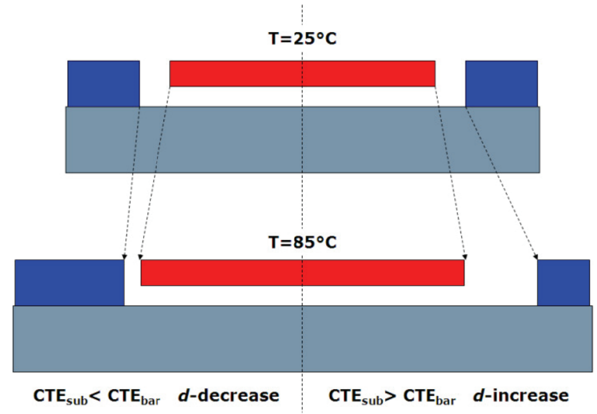

Figure 7 Evolution of the transduction gap for increasing temperature in the cases of substrate expansion smaller/larger than resonator expansion assuming $d <<< W$

Expressing in (3) the temperature-dependence of V_{PI}, and imposing a zero-slope of $f_{res}(T)$ in $T=T_0$ delivers the condition (5) linking normalized material properties, bar dimensions and working point at $T=T_0$ such that f_{res} is locally independent of T. This condition can be fulfilled for typical materials provided $CTE^*_{sub}>1$. Note thus that silicon bars produced on silicon substrates, i.e. typical SOI implementation, cannot be compensated through this scheme.

$$-ET^*_{bar} = 1+\frac{\alpha}{27}\left(\frac{V}{V_{PI\_0}}\right)^2\left\{3\left[CTE^*_{sub}+\frac{W_0}{2d_0}\left(CTE^*_{sub}-1\right)\right]-2\right\} \qquad (5)$$

$$ET^*_{bar} = \frac{ET_{bar}}{CTE_{bar}} \qquad (6)$$

$$CTE^*_{sub} = \frac{CTE_{sub}}{CTE_{bar}} \qquad (7)$$

$$V_{pi\_0} = \sqrt{\frac{16}{27}\frac{E_0 d_0^3}{\varepsilon_0 W_0}} \qquad (8)$$

To demonstrate the compensation of a silicon MEM resonator, Figure 8 shows the temperature-dependence of the bar from Figure 1 processed in this case on sapphire. Two bias points are presented that compensate the T-drift at different temperatures. Using (5), the working point for compensation at 25°C is computed to be V=181.36V. In this case, the total drift of f_{res} over the range -40°C to 85°C lowers from the intrinsic 2966ppm to 94ppm. In the best condition, for V=180.75V, the drift lowers further to a minimum of 82ppm. The bias voltage can be used to account for process inaccuracies and to select the temperature of ideal compensation.

However the previous example is in principle valid, it requires large bias voltages, close-to V_{PI}, while the validity of (3) is limited to V<<V_{PI}. In order to lower the DC-bias voltage V, and more precisely its value compared to the pull-in voltage V_{PI}, the condition (5) defines two options. Either the material properties of the substrate-resonator combination can be modified or the resonator and transduction gap can be redesigned to increase the ratio

W_0/d_0. Consider for example the device simulated in Figure 9. Wider, with W=200µm, 45V suffice to compensate its temperature-drift at 25°C.

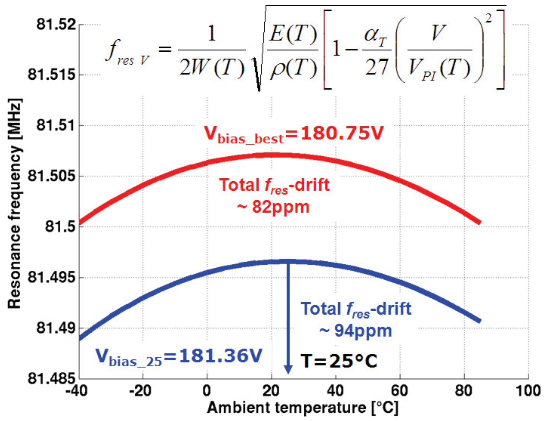

Figure 8 Passive T-compensation of the bar from Figure 1 with identical characteristics as in Figure 4 and Figure 5 at T=25°C and in optimum conditions for the full T-range considered - CTE_{sub}=4.3e-6ppm/°C (sapphire)

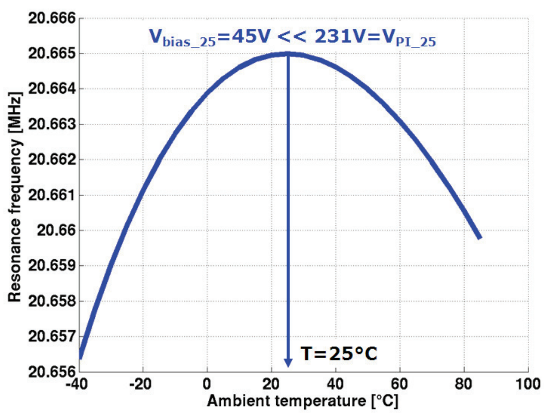

Figure 9 Passive temperature-compensation of bar resonator at room temperature with low voltage compared to the room temperature DC pull-in voltage - W_{25}=200µm

As a final remark, note that the previous developments, presented in the case of electrostatically transduced resonators, can be directly transposed to the magnetic transduction of MEM resonators. For this, the quantities V (voltage), q (charge) and ε (permittivity) have simply to be substituted with nI (total winded current), f (magnetic flux) and µ (permeability).

4 CONCLUSIONS

In this paper, we proposed a novel passive compensation of the temperature-drift of electrostatically-driven MEM-resonators. Key in our implementation is the temperature-driven modulation of the transduction gap that, controlled by design and bias voltage, can fully balance the T-drift due to the intrinsic material properties of the resonator. The further selection of the optimum bias working point allows compensating for potential processing inaccuracies. We applied this scheme to bulk-mode bar resonators and derived a condition for full temperature-stabilization. In case of 80MHz Si-bars, we simulated an improvement of the T-drift between -45°C and 85°C from an intrinsic value of 2966ppm to 82ppm by processing the device on a sapphire substrate and selecting a bias point equal to 180.75V.

REFERENCES

[1] C. Nguyen, "MEMS technology for timing and frequency control," IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, vol. 54, no. 2, pp. 251-270, Feb. 2007

[2] S. Stoffels, S. Severi, R. Vanhoof, R. Mertens, R. Puers, A. Witvrouw and H.A.C. Tilmans, "Light sensitive SiGe MEM resonator for detection and frequency tuning applications", Tech. Digest IEEE Int. MEMS Conf., pp. 691-694, Jan. 2010

[3] G. Bahl, R. Melamud, B. Kim, S. Chandorkar, J. Salvia, M. A. Hopcroft, R. G. Hennessy, S. Yoneoka, C. M. Jha, G. Yama, D. Elata, R. N. Candler, R. T. Howe, and T. W. Kenny, "Observations of fixed and mobile charge in composite MEMS resonators," presented at Hilton Head, USA, June 2008

[4] K. Nakamura, H. Sasaki, H. Shimizu, "ZnO/SiO2-diaphragm composite resonator on a silicon wafer", IEEE Electron. Lett. 17 (1981) 507

[5] J. Salvia, R. Melamud, S. Chandorkar, H.K. Lee, Y.Q. Qu, S.F. Lord, B. Murmann, T.W. Kenny, "Phase Lock Loop Based Temperature Compensation for MEMS Oscillators," Tech. Digest IEEE Int. MEMS Conf., pp.661 – 664, Jan. 2009

[6] W.T. Hsu and C.T.C. Nguyen, "Stiffness-compensated temperature-insensitive micromechanical resonators," Tech. Digest IEEE Int. MEMS Conf., pp. 731-734, Jan. 20-24, 2002

[7] H. C. Nathanson, W. E. Newell, R. A. Wickstrom, and J. R. DAVIS, "The Resonant Gate Transistor", IEEE Transactions on Electron Devices, vol. ED-14, no. 3, March 1967

[8] H. A. C. Tilmans, 1993 "Micromechanical sensors using encapsulated built-in resonant strain gauges", PhD Dissertation Faculty of Electrical Engineering, University of Twente