COMPOSITE FLEXURAL MODE RESONATOR WITH REDUCED TEMPERATURE COEFFICIENT OF FREQUENCY

R. Melamud, B. Kim, M. A. Hopcroft, S. Chandorkar, M. Agarwal, C. Jha, S. Bhat, K. K. Park, and T. W. Kenny

Departments of Mechanical and Electrical Engineering, Stanford University
Stanford, CA, USA

ABSTRACT

This paper reports a method to passively reduce the native temperature coefficient of frequency (TCF) by creating a Silicon - Silicon Dioxide (Si-SiO₂) composite resonator whose bending stiffness has reduced sensitivity to temperature. Silicon exhibits softening with increasing temperature. Amorphous silicon dioxide exhibits an anomalous hardening with increasing temperature. An optimal combination of Si-SiO₂ in flexural mode resonators is determined that would yield zero TCF. Composite single anchor, double ended tuning forks (DETF) were fabricated and show a greater than 10x reduction in TCF in the 15°C to 70°C temperature range. The composite beam resonators were fabricated in our wafer-scale encapsulation process, which is described by [1] and is being commercialized.

INTRODUCTION

To become a viable replacement for the ubiquitous quartz crystal technology, silicon resonators must have a frequency stability of under 100 ppm in the 0°C to 70°C temperature range. Silicon resonators exhibit a native temperature coefficient of frequency (TCF) of -30 ppm/°C that is dominated by the decrease of the resonator stiffness due to the material softening of Silicon.

Current compensation methods can be classified as either active or passive. Active compensation techniques such as ovenization [2] and electrostatic tuning [3] require power in order to reduce the TCF into the desirable range. Passive compensation methods attempt to reduce the native TCF without application of power. Previous passive compensation techniques [4,5] have used axial stress induction in flexural mode resonators to shift the natural frequency. This was accomplished by using materials with different coefficients of thermal expansion (CTE) that would induce thermal stresses with changes in temperature. Although these methods demonstrated the ability to reduce TCF, introducing materials with mismatched CTE's can cause stress induced hysteresis, processing difficulties due to large thermal stresses, restrictions on material selection for clean processes, and undesirable sensitivity to package stress.

This paper reports a method to passively reduce the native TCF by creating a Silicon - Silicon Dioxide composite resonator whose bending stiffness can be insensitive to temperature variation. Silicon dioxide exhibits an anomalous temperature coefficient of Young's Modulus (TCE) that is positive [6]. By combining it with Silicon, which has a negative TCE, it is possible to reduce the temperature dependence of the stiffness of the resonator. Furthermore, this method does not use stress induction as the means to compensate frequency.

THEORY

Flexural mode beam-type resonators, such as the double end tuning forks used in this paper (Fig. 1), that are fabricated from a single material and are single anchored have a frequency and

Figure 1. Single anchor, DETF with outer excitation electrodes and an inner sense electrode.

TCF described in Equation 1. Equation 1.b ignores the smaller effect of dimensional changes with temperature and assumes linear material properties.

$$f = \frac{\beta^2}{2\pi L^2} \sqrt{\frac{B}{\rho A}} = \frac{\beta^2}{2\pi L^2} \sqrt{\frac{EI}{\rho A}} \quad 1.a$$

$$TCF = \frac{1}{f_0} \frac{\partial f}{\partial T} \approx \frac{1}{2} \frac{\partial f}{\partial B} \frac{\partial B}{\partial T} \approx \frac{TCE}{2} \quad 1.b$$

In the above equations, β is the mode constant, E is the Young's Modulus, ρ is the density of the material, I is the flexural rigidity, L is the length of the beam, A is the cross sectional area of the beam, $B = EI$ is defined as the bending stiffness of the beam, f_0 is a reference frequency, and TCE is the temperature coefficient of Young's modulus of the beam's material. The TCE of Silicon is approximately -60 ppm/°C which results in a TCF of -30 ppm/°C for Silicon resonators.

For a composite beam of N materials, the above equations are modified such that the bending stiffness takes into account the geometric composition of the beam (Eq. 2a).

$$B = \sum_{j=1}^N E_j I_j \quad 2.a$$

$$TCF \approx \frac{1}{2} \left[\frac{\sum_{j=1}^N E_j I_j TCE_j}{\sum_{j=1}^N E_j I_j} \right] \quad 2.b$$

The resulting modified TCF is a function of the TCE of each of the materials in the composite. By using amorphous SiO₂, which has a positive temperature coefficient of Young's Modulus (TCE) of +195 ppm/°C, in combination with Silicon, it is possible to design an ideal composite beam whose bending stiffness does not change with temperature yielding a zero TCF resonator.

From the above equation, the only design parameter that can be controlled is the flexural rigidity of each material. For a Si-SiO₂ composite, the optimal configuration requires the minimal amount of SiO₂ growth in order to achieve zero TCF. Several configurations have been considered (Fig 2). A laminate type structure (Fig 2.a) has a flexural rigidity that is linearly related to the thickness of the SiO₂. However, an encapsulated structure (Fig 2.b) has a quartic dependence on thickness of the SiO₂. The latter configuration was chosen since it is most sensitive to SiO₂ thickness and can be easily achieved by oxidizing all exposed Silicon surfaces. Figure 3 shows the result of evaluating the composite beam TCF equation (Eq. 2.b) for the optimal

configuration (Fig 2.b). The target thickness necessary to achieve zero TCF depends on the width of the beam. The model also took into account the orientation dependent oxidation of the beam surfaces as well as the consumption of Silicon during oxidation ($0.46\mu\text{m}$ of Si for $1\mu\text{m}$ of SiO_2) [7].

Figure 2. Cross-section of the DETF through the beams of the resonator. The TCF of the composites will depend on the thickness of the SiO_2 layers. (a) Laminate construction with SiO_2 sandwiched between Si layers. (b) SiO_2 coated Si by oxidation of all Si surfaces. The oxidized configuration is optimal since the flexural rigidity, I , of the SiO_2 is most sensitive to the thickness of SiO_2

Figure 3. SiO_2 thickness on sidewall of beam versus TCF for oxidized silicon resonator configuration (Fig 2.b). This model takes into account orientation dependent oxidation rates and consumption of silicon during oxidation. The target oxidation depends on the initial width of the Si beam. The constants used in this model are: $TCE_{\text{Si}} = -60 \text{ ppm}/^\circ\text{C}$, $TCE_{\text{SiO}_2} = +195 \text{ ppm}/^\circ\text{C}$, $E_{\text{Si}} = 168 \text{ GPa}$, $E_{\text{SiO}_2} = 70 \text{ GPa}$, $h = 20\mu\text{m}$.

FABRICATION AND EXPERIMENTS

Si- SiO_2 composite resonators were fabricated using a wafer scale polysilicon encapsulation with oxide seal processes described in [1]. The only modification was a 30 minute wet oxidation at 1100°C to oxidize the surfaces of the resonator beams. The oxidation occurred after the resonator was released by HF vapor etching of the sacrificial oxide. The thickness of the oxidation was approximated by measuring the SiO_2 thickness ($0.44\mu\text{m}$) on the surface of the encapsulation. The oxidized resonators, with $7.5\mu\text{m}$ beam widths, were measured at 40°C and over a 15°C to 70°C temperature range using a temperature controlled oven.

The oxide seal process used for these preliminary experiments is not as clean as our high temperature epi-polysilicon seal. Devices sealed in this process were operated at a fixed 40°C temperature for 3 hours and showed a positive frequency drift of

$\sim 11 \text{ ppm/hr}$. This drift is attributed to migration of absorbents off of the resonators. The drift is slow enough to allow our first experiments on the temperature dependence of frequency for oxide/silicon composite beams.

Frequency versus temperature data was taken for five cycles over a temperature variation from 15°C to 70°C . The experiment took place over a continuous 15 hr time span and a $+9.9 \text{ ppm/hr}$ drift was observed. The total frequency excursion during this time span was 260 ppm. However, approximately 150 ppm is attributed to a linear frequency drift over time. Figure 4 shows the frequency versus temperature data for the five cycles as well as a comparison to the native TCF of a silicon DETF.

Figure 4. Frequency vs. temperature variation of an oxidized DETF over five cycles from 15°C to 70°C . The total frequency excursion, over a 15 hr span, was 260 ppm. However, approximately 150 ppm could be attributed to a $\sim 10 \text{ ppm/hr}$ drift.

CONCLUSION

Preliminary results show that it is possible to passively reduce the TCF of silicon resonators by incorporating Silicon Dioxide into the structure of the resonator. A relation for the TCF of a composite beam is developed and it is shown that the optimal composite configuration is achieved by oxidation of the surfaces of the silicon resonator. Devices were fabricated in a wafer-scale oxide seal processes and show a 10x reduction in the native TCF compared to single material Silicon resonators. In future work, a combination of passive and active compensation will be used to achieve a TCF less than 1 ppm over this same range.

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