ELECTROSTATIC – TUNING OF HERMETICALLY ENCAPSULATED COMPOSITE RESONATOR

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ABSTRACT

MEMS resonators have promising future as frequency references with high levels of stability. In this paper, we present electrostatic-tuning of frequency for temperature compensation in Si-SiO₂ composite resonators. This tuning technique uses the spring-softening effect for compensation. It is implemented by adjusting the DC bias voltage applied to the resonant structure. Electrostatic-tuning of silicon MEMS resonators has proven difficult because of the very large temperature induced frequency variation that must be overcome (2000 ppm). Si-SiO₂ composite resonators have at least 10x less frequency variation over temperature, and lend themselves to electrostatic-tuning for compensation. This paper presents our first results for a tuning-based compensation approach over a full (70°C-wide) commercial temperature range.

INTRODUCTION

Silicon MEMS resonators have been considered as replacements for quartz crystal references in electronic products and systems [1]. Silicon resonators have many advantages over quartz references such as small size, low cost, less power consumption, and CMOS compatibility. Therefore, MEMS resonators are suitable for frequency references in miniaturized handheld electronic devices that have a large and growing market.

Although micro-machined silicon resonators have many promising attributes, commercial success depends on frequency stability comparable to quartz references; hence, research has been directed toward guaranteeing quartz-level frequency stability of MEMS resonators. The long-term stability of MEMS resonators was proven to be superior to that of quartz references [2]. This becomes possible due to recently developed 'epi-seal' encapsulation technology that provides a hermetic environment for resonator operation. Unfortunately, however, the resonant frequency of silicon resonators has a strong dependency on temperature since the Young's modulus of silicon is a strong function of temperature. The temperature coefficient of frequency (TCf) of silicon resonators is about -30 ppm/°C. This results in ~2000 ppm frequency variation over 70°C-wide range while AT-cut quartz crystals have less than 30 ppm variation over the same temperature range. Therefore, compensating resonant frequency variation over ambient temperature change is a significant remaining problem to meet stability criteria.

Several methods have been proposed to overcome the effects of temperature. An encapsulated micro-oven inside the silicon die has achieved frequency stability better than ±0.1 ppm [3]. But, temperature control can require several mW of extra power consumption to maintain temperature of the resonant beams at the lowest ambient temperatures. Electrostatic-tuning of silicon resonators with sub-micron gaps (~100 nm) [4,5] has been demonstrated; however, bias-induced nonlinearities can be problematic, and the demonstrated frequency stability with this method is generally worse than 10 ppm. This is not enough to compete with widely used temperature compensated crystal oscillator (TCXO) which show ±0.5 ppm to ±5 ppm error. Material compensation using a Si-SiO₂ composite structure [6] and thermal expansion induced stress [7] has been demonstrated.

Although they are able to improve the inherent temperature stability, the frequency stability does not meet commercial product level requirements. Therefore, a new method that can achieve TCXO level stability with minimal additional power is imperative.

This work combines electrostatic-tuning and material Si-SiO₂ compensation to achieve TCXO level performance in a MEMS resonator with low power by taking advantages of both techniques. Electrostatic-tuning uses the spring-softening effect, and it only requires an adjustable bias voltage (V_{bias}). Therefore, this method does not need significantly added power for compensation. However, electrostatic-tuning on our encapsulated silicon resonators is practically infeasible because of the relatively weak spring-softening effect that results from the micron-level electrostatic actuation gap. A sub-micron gap is needed to have strong spring-softening effect to overcome 2000 ppm frequency variation for tuning, but the 'epi-seal' process does not allow it. The recent development of Si-SiO₂ composite resonators [6] makes this method feasible since the composite resonators have inherently 10x smaller frequency variation than silicon resonators. In short, a weak spring-softening effect is good enough to apply electrostatic-tuning on composite resonators. In this paper, results from the combination of a composite resonator and electrostatic-tuning are presented that achieve commercial grade frequency stability.

THEORY

Si-SiO₂ composite resonators

Hermetically encapsulated flexural mode Si-SiO₂ composite resonators (Fig. 1) are fabricated using the 'epi-seal' technology introduced in [8]. The process results composite resonators that have thermal oxide coating on silicon resonant beams. For electrostatic actuation, V_{bias} is applied to the resonant structure through its anchor and an AC signal (V_{AC}) is provided to two input electrodes. The output signal is detected by capacitive sensing. The resonator structure and electrodes for actuation and sensing are buried under epitaxial poly-silicon layer that provides hermetic encapsulation.

Figure 1: Left: Double-end tuning fork (DETF) type composite resonator for electrostatic-tuning. The beam length is 200 μ m, width is 6 μ m, and thickness is 20 μ m. Gap between resonant beam and electrode is 1.5 μ m. The resonant frequency is ~1.126MHz and $Q \sim 12,000$. Right: cross sectional view of the resonant beams of the Si-SiO₂ composite resonator.

Figure 2: Frequency-Temperature curves of typical silicon and Si-SiO₂ composite resonators. For 30°C-100°C temperature range, the frequency variation of the composite resonator is ~200ppm while that of the silicon resonator is ~2000ppm.

Figure 3: Control loop for the electrostatic-tuning. Ambient temperature is measured, and this value is used to find the appropriate V_{bias} from the look-up table. The loop is designed to run once in every second.

The resonant frequency of a beam is given by:

$$f \propto \begin{cases} \sqrt{E_{Si} I_{Si}} & : \text{silicon resonator} \\ \sqrt{E_{Si} I_{Si} + E_{SiO_2} I_{SiO_2}} & : \text{Si-SiO}_2 \text{ resonator} \end{cases} \quad (1)$$

where f is the resonant frequency, E is a Young's modulus, and I is a second moment of inertial. The Young's modulus of silicon is a strong function of temperature; therefore, the bending stiffness of silicon beam varies a lot with change of temperature, and so does its resonant frequency. The Young's modulus of SiO₂ also has a strong dependency on temperature, but it has the opposite trend; Young's modulus of SiO₂ increases as temperature increases while that of silicon decreases. By growing an appropriate thickness of SiO₂ coating as shown in Figure 1, we can tune the overall bending stiffness of the Si-SiO₂ composite beams to be less sensitive to temperature variation. In this way, frequency variation can be reduced on the composite structure. Figure 2 shows typical frequency-temperature (f-T) characteristic of silicon resonators and Si-SiO₂ composite resonators. Over a wide temperature range, the frequency variation of the composite resonator is reduced by an order of magnitude.

Electrostatic-tuning

Electrostatic-tuning uses the spring-softening effect in electrostatic actuation. By changing V_{bias} applied to resonant beams, the effective stiffness of the beams can be adjusted; therefore, this effect is called the spring-softening effect. Since we can modify the effective stiffness, the resonant frequency can be tuned by some amount. So, the spring-softening effect can be

Figure 4: Multiple measurements of the resonant frequency at various temperature and bias voltage for characterization of device. 7 curves at each bias voltage look like one curve due to the consistent response of the resonator.

utilized for temperature compensation. The frequency sensitivity to V_{bias} of parallel plate resonators is given by:

$$\frac{df}{f_0 dV_{bias}} = \frac{-2\epsilon A_e V_{bias}}{k_m d^3} \quad (2)$$

where A_e is area of electrode, k_m is mechanical stiffness, and d is the size of the gap between the resonant beam and the electrode. As shown in equation 2, the sensitivity is a function of dimension and V_{bias} . The sensitivity of our device at usual operating condition ($V_{bias} \sim 20$ V) is about 200 to 400 ppm/V, therefore; 1 V change of V_{bias} is necessary to compensate 200 ppm variation of composite resonators.

The most important thing in electrostatic-tuning is applying the proper V_{bias} at a given temperature that shifts the frequency to the target frequency. Therefore, a look-up table that has a list of temperature points and corresponding V_{bias} values to achieve constant target frequency is necessary. This look-up table can be built through device characterization. With a look-up table, electrostatic-tuning is implemented as an open loop control as shown in Figure 3.

CHARACTERIZATION

Repeatability check

Having a good look-up table is the most important requirement for open loop control. Therefore, the Si-SiO₂ composite resonator was characterized and analyzed to build a reliable look-up table from the relationships between ambient temperature, V_{bias} and frequency. The resonant frequency of the composite resonator is measured several times at various temperature and V_{bias} conditions (Fig. 4). As predicted in equation 2, the resonant frequency decreases as higher V_{bias} is applied. Frequency data is analyzed carefully to verify repeatability. Analysis is performed to check whether the measured frequency deviation comes from environmental changes or drifting device characteristics. Since temperature deviation and noise in V_{bias} are the two most dominating environmental factors that cause frequency variation, analysis is based on those two variables.

Figure 5: Measured and estimated deviation of frequency at 19V and 20V. Uncertainty analysis is done with those two voltages since they have comparably large frequency deviation.

Figure 6: Surface plot of the empirical equation that describes the resonant frequency as a function of bias voltage and ambient temperature.

Figure 7: Look-up table for several target frequencies.

First, standard deviation of the measured frequencies at each temperature and V_{bias} condition are plotted. Afterwards, it is compared with estimated standard deviation of frequency (Fig. 5). The estimation is based on the uncertainty analysis given by:

$$\sigma_f = \sqrt{\left(\frac{\partial f}{\partial T} \sigma_T\right)^2 + \left(\frac{\partial f}{\partial V_{bias}} \sigma_{V_{bias}}\right)^2} \quad (3)$$

where f is the resonant frequency, T is temperature, and σ is standard deviation. It is true that there are some other minor factors that affect the resonant frequency, but they are neglected since their effects are negligible and it is difficult to identify them. As shown in Figure 5, the measured standard deviation of frequency and estimated standard deviation of frequency do not match perfectly; however, we can see that they show the same trend of deviations with values in a similar range. Considering other minor factors that are neglected in the estimation, we can conclude that frequency-temperature-bias voltage relationship is repeatable.

Look-up table

The look-up table is built after the repeatability of characterization is guaranteed. First, the frequency is plotted as a function of bias voltage and temperature. Next, two variable polynomial fitting is performed to obtain an empirical equation. The empirical equation is plotted on Figure 6. The empirical equation is obtained because it helps to get intermediate values that are not measured in characterization run. The two variable polynomial fitting is based on equation given by:

$$f = \sum_{j=0}^5 \sum_{i=0}^5 a_i b_j T^i V_{bias}^j \quad (4)$$

where $a_i b_j$ is fitting coefficient.

The order of the polynomial equation is decided after error analysis. The maximum error between measured data and fitted data is targeted to be sub-ppm to achieve TCXO level stability. A 5th order polynomial is chosen according to the criteria. From the polynomial equation, a look-up table that has a list of temperatures and bias voltages for several target frequencies (Fig. 7) is built by finding the iso-frequency lines.

Experimental setup

A resonator chip and a Platinum RTD are mounted on a PCB and placed in a temperature-controlled chamber. An oscillator circuit is connected to the resonator to sustain oscillation. An Agilent 34420A nano volt/micro ohm meter is connected to the

Figure 8: Experimental setup for electrostatic-tuning.

Figure 9: Results from electrostatic-tuning on the composite resonator.

RTD to read the temperature of the resonator and an Agilent 53132A universal counter is connected to the oscillator circuit to get the resonant frequency. A Keithly 236 current/voltage source is wired to the resonant beam to supply stable voltage. Resolution of the Keithly 236 is 10 mV in the voltage range of interest. Considering the frequency sensitivity to resonator V_{bias} , the tuning resolution is given as 2 to 4 ppm. The ± 5 V power supply for the oscillator circuit and the computer that runs control code are omitted in Figure 8.

RESULTS

The full experiment was performed 3 times and frequency was maintained within ± 3.2 ppm from the target frequency over a wide temperature range (Fig. 9). The demonstrated result is in the level of stability of commercial TCXO [9], and it is a 6x improvement over the previous electrostatic-tuning result [5]. If we consider that the tuning resolution is 2 to 4 ppm, ± 3.2 ppm is within the expected resolution. Also, it implies that there is a room for further improvement of temperature stability with a more precise voltage source for V_{bias} .

Unlike the combination of micro-oven and Si-SiO₂ composite resonator [3], the reported method doesn't require additional power consumption but can still achieve commercial level frequency stability. In addition, temperature gradients are not generated on resonator chip since heat source such as micro-oven does not exist inside the chip; therefore, a relatively simple temperature sensor, unlike complicated ones [10,11] for ovenized devices, is good for temperature sensing. Relatively easy temperature sensing can be another benefit of electrostatic-tuning. Furthermore, this method has an advantage of programmable output frequency; a single device can generate various frequency outputs if a look-up table that has several target frequencies (Fig.7) is used.

CONCLUSIONS

We have first demonstrated electrostatic-tuning on Si-SiO₂ composite resonator to achieve TCXO level temperature stability. With other advantages such as less power consumption, simple temperature sensing, and programmable output frequency, electrostatic-tuning of composite resonators becomes a promising technology for commercialization of MEMS resonators.

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