FREQUENCY STABILITY OF WAFER-SCALE ENCAPSULATED MEMS RESONATORS

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ABSTRACT

This paper presents an investigation of the long-term frequency stability of wafer-scale encapsulated silicon MEMS resonators. Two aspects of stability were examined: long-term stability over time and temperature-related hysteresis. Encapsulated resonators were tested over a period of 8,000 hours in constant environmental temperature of 25°C ± 0.1°C. No measurable drift, burn-in time, or other changes in resonant frequencies were detected. Another experiment was performed to investigate the stability of the resonators with temperature cycling. The resonant frequency was measured between each cycle for more than 450 temperature cycles from –50°C to +80°C. Additional data is presented for short-term hysteresis measurements –10°C to +80°C temperature cycle. No detectable hysteresis was observed in either of the temperature cycle experiments. These series of experiments demonstrate resonant frequency stability of wafer-scale silicon based MEMS resonators.

Keywords: MEMS resonator, long-term stability, resonant frequency stability, encapsulation, hysteresis

INTRODUCTION

Resonators are one of the key elements in communication engineering. Currently quartz is the most widely used resonator material. However, its high energy consumption and relatively bulky size limit the possibilities for reduction in circuit volume and manufacturing cost. Recently MEMS resonators have been considered as one of the most interesting candidates to replace quartz resonators for the following reasons: (1) Microfabrication technology contributes not only to reduction in the size of resonator itself but also in the volume of encapsulation that has to be temperature controlled, which results in lower energy consumption. (2) The possibility of integrated frequency references and filters within a silicon IC promises high volume production and reduction in the cost by minimizing number of parts and physical volume of circuitry [1, 2]. However, stability and reliability characteristics of MEMS resonators as practical devices have not yet been sufficiently demonstrated [3, 4] and this fact is limiting the commercial potential of MEMS resonators. Several researchers have reported that encapsulated MEMS resonators provide better resonant frequency stability performance [4, 5]. However, none of them are dealing with wafer-scale encapsulated resonators. Wafer-scale encapsulation has many intrinsic benefits such as high yield, volumetric reduction, improved encapsulation quality, etc. This paper reports the first measured results for resonant frequency stability of silicon resonators fabricated within a wafer-scale encapsulation process. The encapsulation used for this test was processed by applying the recently developed process [6].

FABRICATION

The resonators investigated here were fabricated using a single-wafer polysilicon thick-film encapsulation process. This process involves covering unreleased MEMS devices with a sacrificial oxide layer and a 2 µm thick epitaxial polysilicon encapsulation. The devices are released by etching this sacrificial oxide layer with a vapor-phase HF etch process through vent holes etched on the 2 µm thick silicon layer. Then the encapsulation is sealed by a ~20 µm thick epitaxial polysilicon deposition. Chemical-mechanical polishing (CMP) is applied to reduce the roughness of the thick deposition. Finally, oxide and metal layers are deposited to provide electrical contact and insulation to the resonator. Figure 1 shows the SEM cross section view of the resonator used for the stability test fabricated by the process above described.

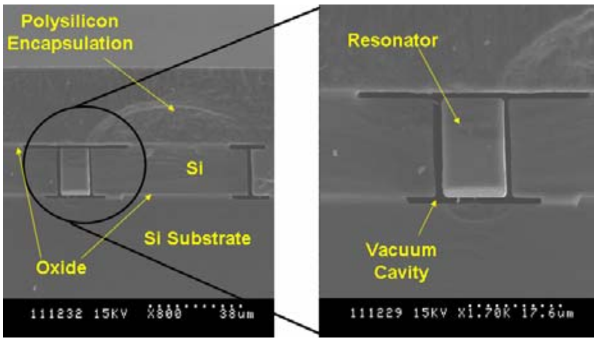

Figure 1. SEM of cross-section view of the resonators used in the stability test. The polysilicon cap layer creates a hermitically sealed enclosure.

The encapsulation creates a hermitic seal for the resonators and insulates them against outside conditions such as particulants, humidity, gases, etc. The quality of this encapsulation was investigated in our previous work [3].

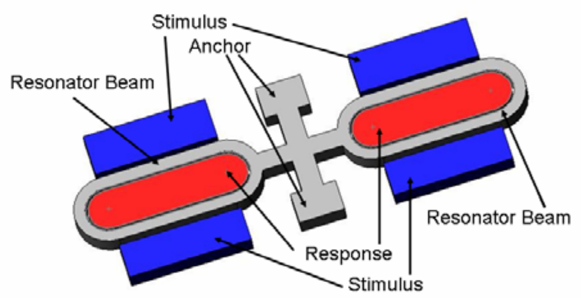

Figure 2. Perspective view schematic of the MEMS resonator used in the resonant frequency stability test. It consists of 2 symmetric double-ended tuning forks anchored in the middle of the structure. This "central anchor" design is intended to isolate the resonator from external layer stresses. The electrostatic driving force is applied at the "Stimulus" electrodes and the resonator output is sensed through the "Response" electrodes.

The resonators described in this paper are actuated and sensed by electrostatic force (Fig. 2), and are specifically designed with a single mechanical support in the middle of the structure to minimize the possibilities of transferring any influence of thermal expansion or residual stress of the layers other than the actual resonator beam layer.

LONG-TERM STABILITY

Long-term frequency drift of these MEMS resonators was examined by monitoring 5 separate resonators. Each resonator was excited and measured approximately every 30 minutes over 8,000 hours (~330 days). To minimize temperature-related frequency variations, the resonators were installed in a temperature-controlled chamber.

To observe the long-term stability of MEMS resonators, Allan deviation is adopted [7]. Allan deviation has been used historically to describe the stability of atomic clocks and quartz oscillators. It uses 2nd differences of frequency rather than differences from the mean to calculate the variations, and is convergent for most clock noises. Allan deviation is defined as:

$$\sigma_{Allan}(t)=\sqrt{\frac{1}{2(N-1)}\sum_{k}^{N-1}(\bar{y}_{k+1}-\bar{y}_{k})^{2}} \tag{1}$$

The Allan deviation curve for one of the MEMS resonators in this experiment is shown in Fig. 3. As shown in the plot, the noise floor is about 0.7 ppm and the entire error has been maintained in ppm range during 8,000 hours long-term operation. Also as shown in Fig. 4, the long-term aging rate of the MEMS resonators housed in this encapsulation is no worse than 0.5 ppm/year, which approaches the performance of TCXO oscillators [8]. In addition, no initial aging or stabilization period was found among any of our monitored MEMS resonators. Typical quartz crystal resonators exhibit 1-10 ppm of burn-in drift during the first few days to weeks of operation [8]. This absence of initial aging indicates that there is a negligible amount of contamination transfer effects or residual stress on our silicon-based wafer-scale encapsulated MEMS resonators.

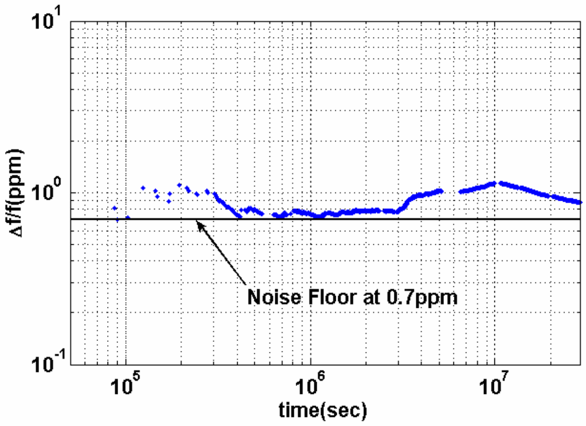

Figure 3. Allan deviation plot for one of the monitored resonators. During 8,000 hrs long-term measurement, error deviation has been maintained at ppm ranges.

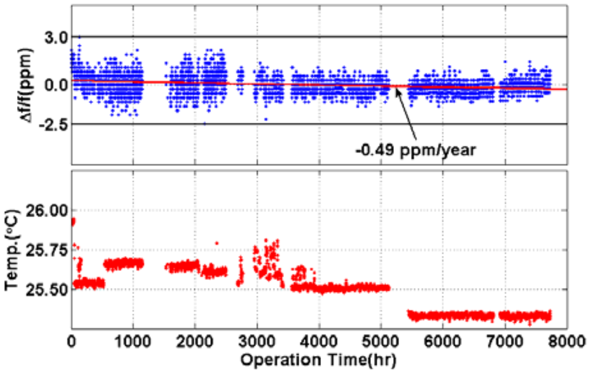

Figure 4. Plot of resonant frequency vs time for one of the monitored resonators for long-term aging test. During 8,000 hrs operation, the worst-case aging rate, shown by the fit line, is less than 0.5 ppm/year. The lower is the plot for measured temperature. The discontinuities in the data represent periods when the test was stopped for maintenance or improvement. Small differences in the ground level during each test period caused the slight difference in absolute value of the output voltage of the temperature sensor in each test period (1~2 mV offset of ground level, which corresponds to 0.1~0.2°C offset). After accounting for this ground level shift, the actual temperature drift is ±0.025°C, which is due to the control limit of the temperature chamber used for the experiments.

However, given that the temperature inside of the chamber drifted approximately ±0.025°C and the temperature coefficient of frequency (TCf) of the resonators is about –27 ppm/°C, variability in the chamber temperature should yield about ±0.675 ppm drift in resonant frequency. This matches with the noise floor value found in Allan deviation curve (Fig. 3). This uncertainty due to temperature variation, combined with the equipment resolution of 0.33 ppm gives a total ±1 ppm resolution for the long-term resonant frequency measurement. We strongly believe that the performance of the MEMS resonators is better than we are currently able to measure, and we expect that we can show better stability when we improve our measurement techniques in the near future.

TEMPERATURE HYSTERESIS

Two more experiments were performed to examine temperature hysteresis, i.e., the characteristic change in resonant frequency after rapid environmental temperature changes. If there is axial stress on the resonator beam due to thermal expansion, it can cause change in resonant frequencies of MEMS resonators [10] or cracking in the encapsulation. Again, the MEMS resonators used in these experiments are single anchored, thus they are expected to be immune to axial stress derived from differential expansion of layers in the encapsulated silicon die.

The first test measured resonant frequency in between each temperature cycle for more than 460 cycles from –50°C to +80°C (Fig.5 (a)). The temperature inside the chamber ramped up to 80°C and down back to 30°C. After that it was held for 30 minutes to reach thermal equilibrium in the temperature chamber. Then the resonant frequencies of all the MEMS resonators were measured one by one. The temperature was then ramped down to –50°C and back to 30°C to measure the resonant frequencies again.

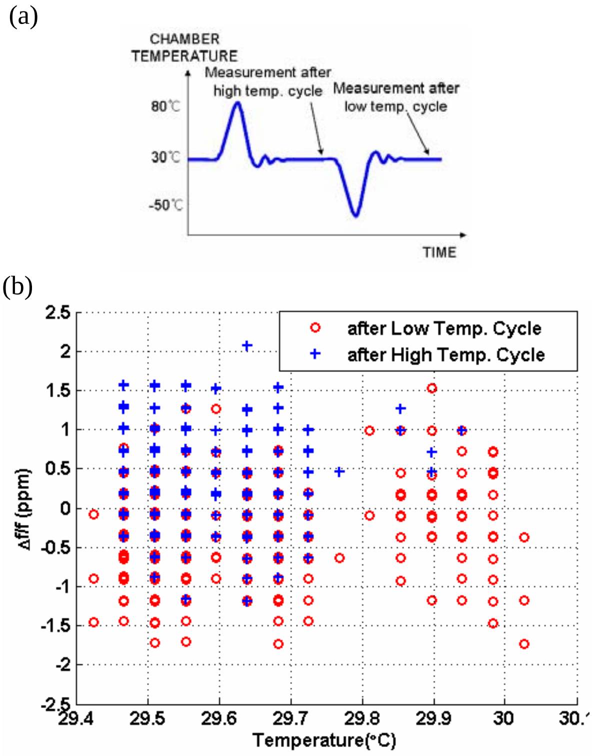

Figure 5
(a) Resonant frequency of the MEMS resonators was measured at 30°C after the temperature inside the chamber was cycled between –50°C and 80°C. Every measurement took place after holding for about 30 minutes to reach thermal equilibrium.
(b) Plot of resonant frequency vs temperature for temperature cycling test. Resonant frequencies are measured at 30°C after high temperature cycle (+) and after low temperature cycle (O). This result suggests absence of hysteresis in these MEMS resonators.

To date, about 460 temperature cycles have been performed over a period of 200 days, and all the measurements were performed at 30±0.1°C. No detectable hysteresis in resonant frequency has been observed (Fig. 5(b)). The difference between the average resonant frequency after high temperature cycles and after low temperature cycles was less than 0.77 ppm. However, the average temperature difference between the two cases was 0.03°C. Given that the temperature coefficient of frequency in these resonators is approximately -27ppm/°C, a frequency shift of 0.95 ppm would be expected for a temperature shift of 0.03°C. Therefore the observed frequency shift is most likely related to slight temperature gradients within the apparatus at the time of the measurements.

Another experiment was performed to measure resonant frequency every 10°C while the temperature was ramping up and down between a –10°C and +80°C. Silicon resonators with the identical design as in the previous experiments were used. The temperature in the chamber was increased in steps of 10°C, and at each step, the chamber was held for 30 minutes and allowed to reach thermal equilibrium and then the resonant frequency was measured. The same process was repeated for decreasing temperature from +80°C to –10°C As shown in Fig. 6, no trend between temperature increasing and decreasing cases has been found.

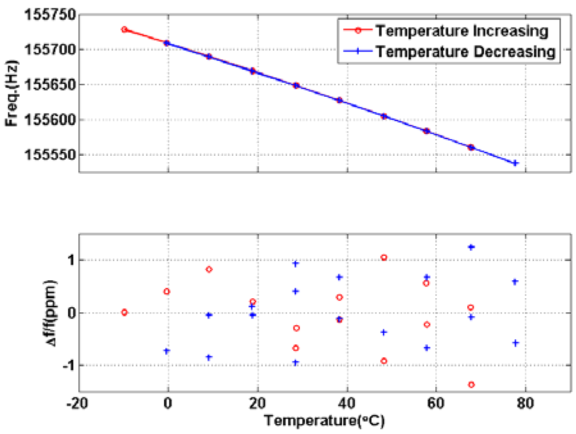

Figure 6 The upper plot shows resonant frequency vs temperature for hysteresis test. The lower plot demonstrates the error of resonant frequencies with respect to the interpolated resonant frequencies at that temperature. So far no trend between temperature increasing and decreasing cases has been found. While cycling the environmental temperature, resonant frequencies are measured every 10°C.

The result from these separate experiments indicate that there is no significant residual stress or differential thermal expansion which might affect resonant frequency stability for rapid changes in environmental temperature.

CONCLUSIONS

For the first time, resonant frequency stability of wafer-scale encapsulated MEMS resonators has been investigated in various ways. We have shown that the long-term aging rate of these resonators is equivalent to commercial quartz crystal resonators. Also, unlike quartz resonators, no initial aging or stabilization period was found. In addition no measurable hysteresis was found.

This improved performance is attributed to the clean, high-temperature fabrication process used to encapsulate these resonators, which suggests that the drift and hysteresis problems observed in other MEMS resonators have never been fundamental, but rather have always been due to their operating environment. Our encapsulation process is able to provide an effective shield for resonant frequency stability for MEMS resonators.

Currently, resonant frequency stability of these resonators with self-oscillating circuits is being examined. With the help of self-oscillating circuits, these resonators will operate continuously at their resonant frequencies. Also, resonant frequency stability related to material fatigue or aging will be investigated in the near future. We plan to build a test set-up which will provide a more stable operating temperature to measure the stability of MEMS resonators. We expect that these improvements will allow us to show more accurate and precise results about resonant frequency stability for MEMS resonators in the near future.

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