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INVESTIGATION OF MEMS RESONATOR CHARACTERISTICS DURING LONG-TERM AND WIDE TEMPERATURE VARIATION OPERATION

Bongsang Kim, Rob N. Candler, Matthew Hopcroft, Manu Agarwal,
Woo-Tae Park, Jeffrey T. Li, and Thomas Kenny

Stanford University
Department of Mechanical and Electrical Engineering
Stanford, CA 94305-4021
bongsang@stanford.edu

ABSTRACT

Two types of single-crystal silicon micromechanical resonators having resonant frequencies at 150 kHz and 130 kHz were tested under harsh environment to investigate stability. To observe long-term stability, the main characteristics, such as resonant frequency and quality factor were measured over 2,500 hrs continuously while maintaining constant environmental temperature at 25℃±0.1℃. A separate experiment was also initiated to show stability during temperature cycling from -50℃ to 80℃. In both experiments, the total change in resonant frequency were less than 10 ppm and quality factor less than 10%, which demonstrates the stability of encapsulated micromechanical resonators upon exposure to harsh environments.

INTRODUCTION

Micromechanical silicon resonators are increasingly important devices due to potential applications as frequency references and filters[1-3]. However, commercialization of these silicon resonators is only beginning. The main focus of our current MEMS resonator research efforts is the stability, reliability, packaging, and tunability of these devices. In order to be used as a frequency reference, MEMS resonators should be able to maintain stability of the resonant frequency under various environment effects such as wide temperature range or long-term operation. While some preliminary studies have been reported[4, 5], there is a lack of good data regarding long-term performance of MEMS resonators. The purpose of this research is to enable our own studies of the characteristics of MEMS resonators upon exposure to various environment conditions.

FABRICATION

The resonators are fabricated by using a wafer-scale encapsulation process[6, 7], which was developed from our previous work in collaboration with researchers from Robert Bosch Palo Alto Research and Technology Center. The resonators are fabricated in silicon-based and IC-compatible MEMS process. Starting with SOI wafer, the device structure is etched with a plasma etch. Then a layer of epitaxial silicon is deposited to encapsulate and the resonator is released with vapor phase HF etch. At the end, a second layer of epitaxial silicon is deposited to complete the final seal.

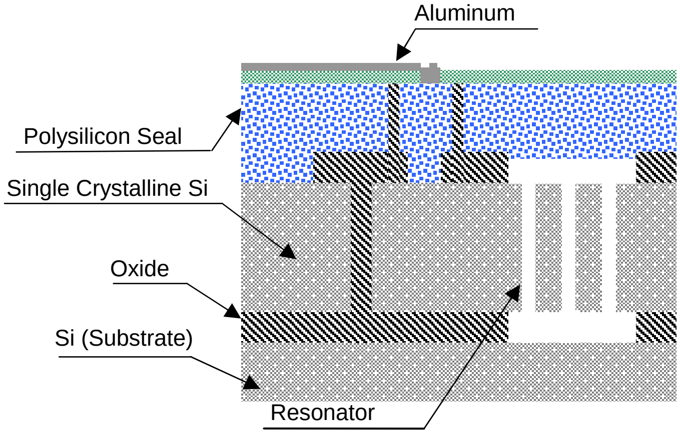

Figure 1 A cross-section of an encapsulated resonator. A resonator made with an SOI wafer is encapsulated by our epi-polysilicon process to maintain atmosphere inside the cavity.

Because all resonators used in this measurement were encapsulated in the same fabrication run, the initial pressure inside all cavities should be identical.

Two resonator designs chosen for these two long-term stability experiments and temperature cycling experiments are shown in Fig 2. The resonators tested were variations of single clamped tuning forks and were selected because of the sensitivity of Q to pressure is the mbar range.

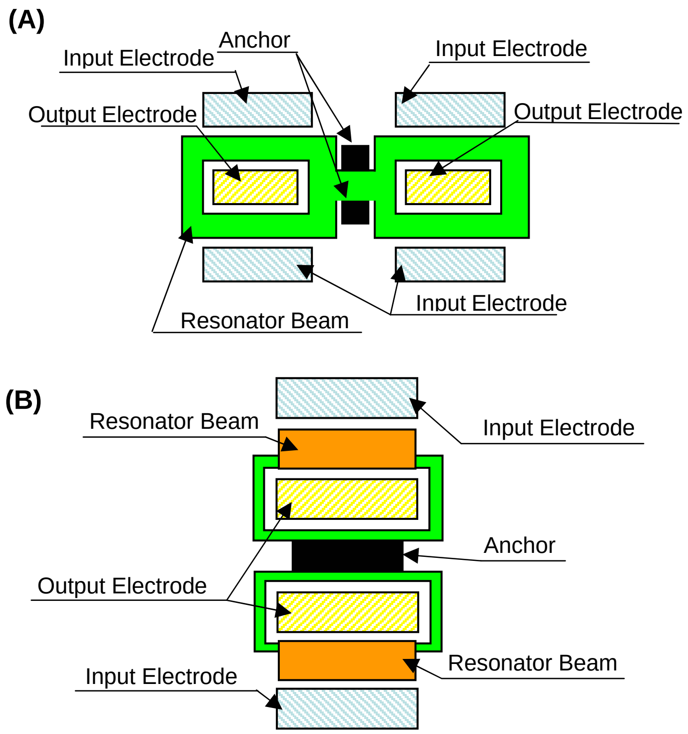

Figure 2 Resonator designs used for the experiments.
(A) Design A - Center-anchored, double-double design. (Frequency~150kHz, Q~33,000)
(B) Design B - Center-anchored, opposing-mass design. (Frequency~130kHz, Q~50,000)

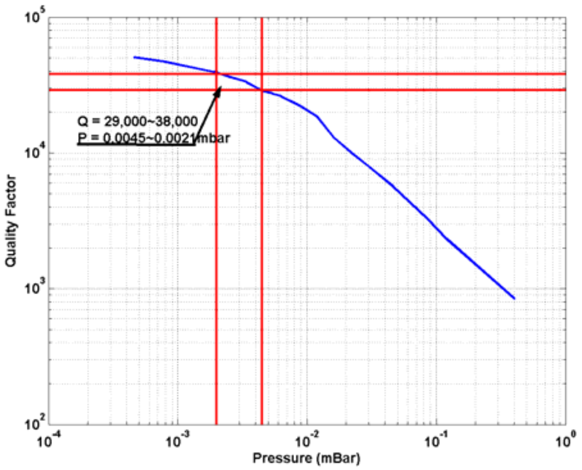

Figure 3 Quality factor vs pressure calibration for unencapsulated device for Design A resonator. This plot shows that quality factor around 33,000 indicates that the pressure inside the cavity is approximately 0.0035 mbar.

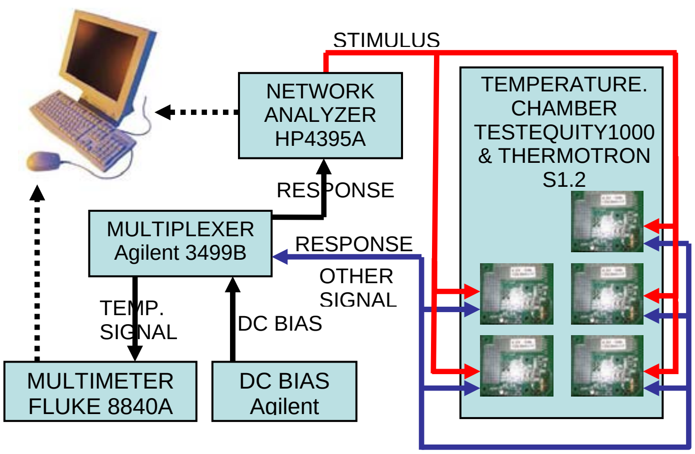

Figure 4 Diagram for experiments setup, A multiplexer is dedicated for parallel measurement. By GPIB connection, all the equipments are controlled by a PC.

LONG-TERM STABILITY

The first experiment was performed to observe possible leakage and aging effects for long-term operation of the MEMS resonators. Although it is known that in absence of hydrostatic confining pressures, silicon displays no dislocation activity even at high stresses, there have been experimental results that have shown that MEMS devices may degrade and fail under cyclic loading condition in ambient air and at room temperature[8]. This aging effect, if it exists, can cause structural changes of MEMS resonators and result would be a shift in resonant frequency.

Another issue we were considering was energy loss due to air damping. There are several energy loss mechanisms for MEMS resonators including air damping, clamping loss through substrate, and thermoelastic dissipation[9, 10]. To achieve high Q, our resonators were encapsulated and the cavity inside was maintained below 0.005 mbar which was the encapsulation pressure that we achieved through the process. However, air leakage through the encapsulation would increase the cavity pressure, increase the energy loss due to air damping, and result in a drop in Q. By measuring Q for the resonators, we could examine this air leakage through the encapsulation during long-term operation.

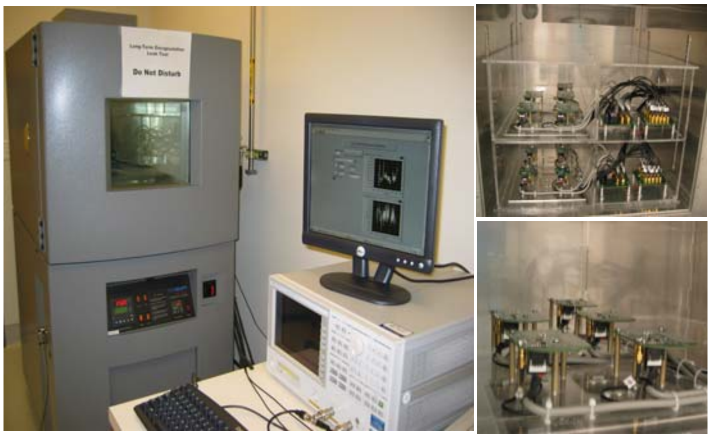

Figure 5 Test setup for long-term stability test. Resonators are installed in parallel in the temperature chamber which maintains the temperature constant environment.

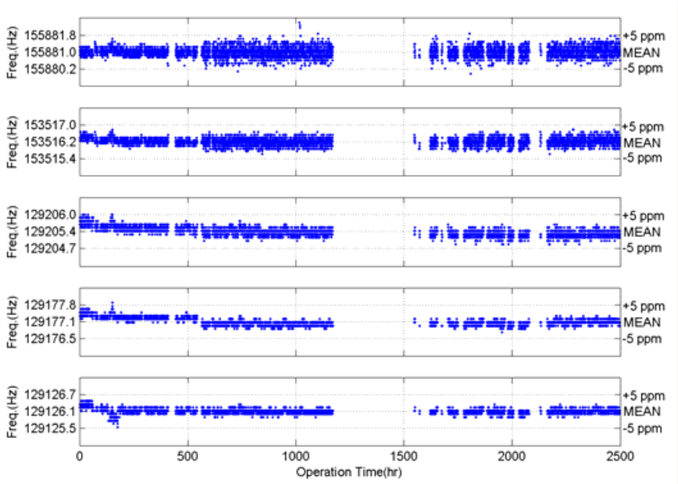

Figure 6 Plot of resonant frequency vs time for 5 monitored resonators. Each row represents a resonator used for long-term stability experiments. During 2,500 hours operation, the resonant frequencies of each resonator drifted by less than 5 ppm.

Five resonators, 2 of *Design A* resonators and 3 of *Design B* resonators, were provided to the experiment test for long-term stability as shown in Fig. 5. To exclude all possibilities other than the effect of long-term operation, the resonators were installed in a TESTEQUITY 1000 temperature chamber, which has maintained the environment temperature at 25℃±0.1℃. A HP4395A network analyzer was used to measure the main characteristics of resonators. Each measurement consisted of 3 separate frequency sweeps, with each sweep iterating to a narrower frequency range. The last sweep spanned 50Hz with 401 data points, which yielded 0.125Hz resolution for the measurement. All 5 resonators were measured in consecutively with a HP3499B multiplexer which connected them with all the other instruments alternately. Every resonator was swept about 150 times a day, resulting in 50 complete measurements for each resonator.

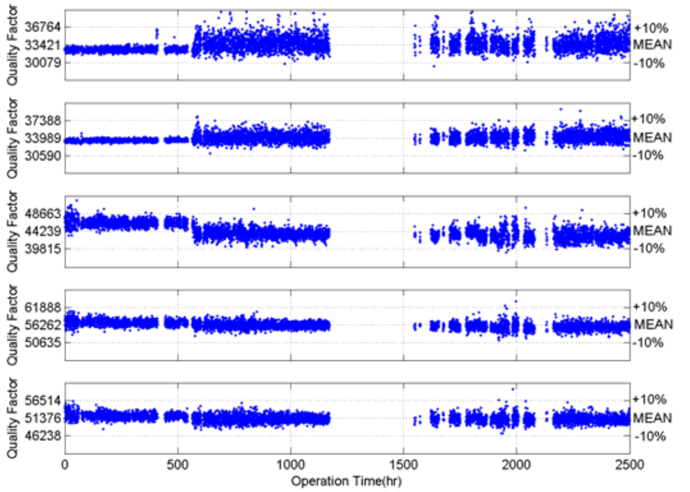

Figure 7 Plot of quality factor vs time for 5 monitored resonators. Each row represents a resonator used for long-term stability experiments. During 2,500 hours operation, the quality factors of each resonator remained within the noise levels of measurements which are ±10% of their original values.

During 2500 hours of operation, we have not seen any evidence of significant changes in frequency for any of the resonators shown in Fig. 6. The variations of resonant frequencies for any resonators are in the range of ±5ppm, which is probably limited by the accuracy of our temperature control thermometers.

Figure 7 shows Q values are also maintained within around ±10% range. These resonators are already more than 9 months old at the time of writing and these Q values are matched with previous Q values which were measured six months ago. These preliminary results demonstrate that the pressure in the encapsulated cavity has been maintained for at least half a year without any measurable leakage. For measurements taken over 9 months, the pressure is maintained with the noise level of 0.001 mbar.

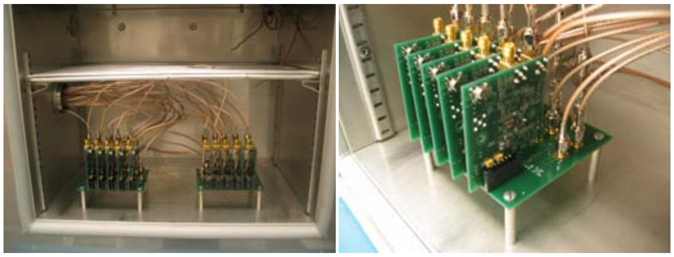

Figure 8 Test setup for long-term stability test. Left is the inside of a Thermotron S1.2 temperature chamber, and right shows the circuit boards and wiring for parallel measurements.

TEMPERATURE CYCLING

The second experiment examined the characteristic changes in MEMS resonators after rapid environmental temperature change. To achieve stability for MEMS resonators, the leak rate must be maintained over a wide temperature range. Also if there is residual stress due to thermal expansion, it can cause change in characteristics of MEMS resonator. The same types of resonators, *Design A* and *Design B*, which were also used for the long-term stability experiment, are used for temperature cycling experiments.

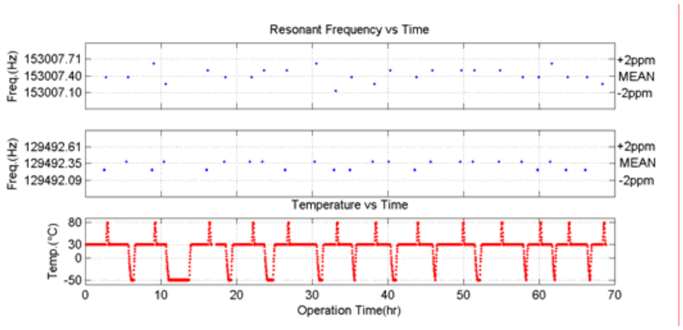

Figure 9 Plot of resonant frequency vs time for 2 resonators monitored for temperature cycle experiments. Resonant frequency was measured when the environmental temperature was maintained at 30℃. During 70 hours of 11 temperature variation cycles, the resonant frequencies of each resonator stayed within ±2ppm of their original values.

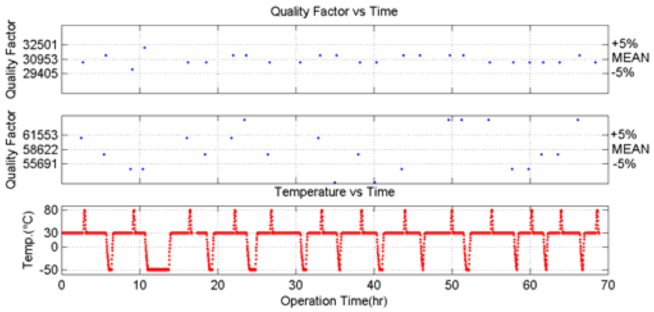

Figure 10 Plot of quality factor vs time for 2 resonators monitored for temperature cycle experiments. Quality factor was measured when the environmental temperature was stable at 30℃. During 70 hours of 11 temperature variation cycles, the quality factors of each resonator stayed closed to their original values.

Another temperature chamber, a THERMOTRON S1.2, was dedicated for the temperature cycling experiment. The chamber ramped up to 80℃ and down back to 30℃. After holding long enough to reach thermal equilibrium, the resonant frequencies and Q of each resonator were measured by a HP4395A network analyzer. Then the temperature went down to -50℃ and came back to 30℃ to measure those characteristic values. To obtain reliable data, these cycles were performed 11 times during this first 70 hours. All the measurements were performed at 30℃±0.1℃.

As shown in Fig. 9 and 10, during 11 temperature variation cycles, the resonant frequency was maintained in the range of ±2ppm and the Q values ±10%. Again no evidence of changes in frequency or Q values for any of the resonators was observed.

CONCLUSIONS AND FUTURE WORK

The main accomplishment of this work is to demonstrate stability of micromechanical resonators in harsh environment. We demonstrated that there has been no noticeable change in main characteristics of micromechanical resonators either for long-term operation or after rapid and wide change of environmental temperature. Our encapsulation process is able to provide an effective shield against harsh environmental conditions. These results are the first step to develop techniques for ultra stable micromechanical resonators operating at harsh environmental conditions.

All of the experiments described in this paper will remain in operation through the time between writing of this manuscript and presentation of the results at the IMECE meetings. At that time we will have more than 5,000 hours of stability data and more than 2,000 hours of temperature cycling data, including almost 4,000 temperature cycles.

ACKNOWLEDGEMENTS

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