Frequency stability of wafer-scale film encapsulated silicon based MEMS resonators

Bongsang Kim*, Rob N. Candler, Matthew A. Hopcroft, Manu Agarwal, Woo-Tae Park, Thomas W. Kenny

Stanford University, Departments of Mechanical and Electrical Engineering, Terman 551, Stanford, CA 94305, USA

Received 20 April 2006; received in revised form 1 October 2006; accepted 13 October 2006

Available online 27 November 2006

Abstract

The stability of resonant frequency for single wafer, thin-film encapsulated silicon MEMS resonators was investigated for both long-term operation and temperature cycling. The resonant frequencies of encapsulated resonators were periodically measured at 25 ± 0.1 °C for >9000 h, and the resonant frequency variation remained within the measurement uncertainty of 3.1 ppm and 3.8 ppm for the two designs of resonators measured. Also, the resonators were temperature cycled for 680 cycles between −50 °C and 80 °C, measuring the resonant frequency each time the temperature reached 30 °C. Again, the change in resonant frequency was seen to remain within the measurement uncertainty. This demonstrates stability of resonant frequency for both long-term operation of more than a year and large number of temperature cycles, emphasizing the stability of both the resonator and the package.

© 2006 Published by Elsevier B.V.

Keywords: MEMS resonator; Long-term stability; Resonant frequency stability; Encapsulation

1. Introduction

Silicon based MEMS resonators are a promising technology for the replacement of quartz resonators, which are currently the dominant technology for many frequency reference applications [1]. Silicon resonators are attractive because the potential for reduced size, cost, and power consumption, as well as integration with circuitry on the same wafer. Also, integration of the resonator structure with the IC can reduce parasitic losses from higher level packaging. This integration will also lead to reduced need for higher level packaging, which is significant when considering that packaging dominates the cost of many devices.

While there have been many breakthroughs in the field of MEMS resonators [2–5], the problem of packaging has not yet been solved. The stability of the resonant frequency over time is absolutely essential for use as a frequency reference, and the frequency stability depends on the quality of the package environment. Early work investigated the long-term stability of MEMS resonators, but the measured stability was insufficient for many applications [6]. Recent work has investigated possible fatigue in thin-film silicon for both single crystal and polysilicon [7,8]; however, fatigue of thin-film silicon is not fully understood and remains controversial [9–12]. Hope has remained that silicon resonators can have sufficient stability for IC references and other applications if low-pressure, water and oxygen-free hermetic packaging is developed [9,13].

We have developed a wafer-scale encapsulation process for MEMS resonators and inertial sensors. Our wafer-scale encapsulation has several possible benefits, including high yield of devices on completed wafers, reduced package size (and therefore cost) due to the lack of a bond ring, and robustness against standard post processing techniques, such as wire bonding, die handling, and injection molding of plastic [14–16]. In addition, we show that our encapsulation process provides an effective seal against air leakage, such that it may provide excellent vacuum condition for MEMS resonators to achieve and maintain high quality factor for long-term operation [17]. Frequency stability towards acceleration and vibration have also been investigated [18]. We believe that the stability of the package environment also leads to stability of resonant frequency. This paper reports the first measured results for resonant frequency stability...
of silicon MEMS resonators fabricated within this wafer-scale thin-film encapsulation process.

2. Fabrication

The resonators investigated here were fabricated using a single-wafer polysilicon thin-film encapsulation process [16,17,19]. This process involves covering unreleased MEMS devices with a sacrificial oxide layer and a 2 μm-thick epitaxial polysilicon layer. The devices are released by etching the sacrificial oxide layer with a vapor-phase HF etch process through vent holes etched in the 2 μm thick silicon layer. The device is then resealed by a ~25 μm-thick epitaxial polysilicon deposition at 950 °C and planarized via chemical–mechanical polishing (CMP). The 25 μm-thick encapsulation is etched to provide isolation for the electrical contacts, which are routed through the highly conductive polysilicon encapsulation. Finally, oxide and metal layers are deposited to provide electrical contact and insulation to the resonator. Fig. 1 shows a schematic of our encapsulation process and Fig. 2 shows an SEM cross-section view of the resonator used for the stability test.

The two resonator designs used in this work are electrostatically actuated and capacitively sensed (Fig. 3). Both the designs are specifically designed with a single mechanical support in the middle of the structure to minimize the possibilities of induced stress from thermal expansion of different materials or residual stress of adjacent layers. The electrostatic driving force is applied at the “Stimulus” electrodes and the resonator output is sensed through the “Response” electrodes, with a DC bias applied to the resonator structure. Temperature coefficient of resonant frequency (TCf), resonant frequency sensitivity to the environmental temperature change, is experimentally acquired as −27 ppm/°C for design A resonators and −33 ppm/°C for design B resonators respectively at room temperature. These values depend on temperature coefficient of Young’s modulus of silicon and resonator geometry. Temperature in a test cham-

---

Fig. 1. The schematic for epi-seal encapsulated device. Resonator is released by HF vapor etching of sacrificial oxide, and epi-poly silicon is deposited to seal the cavity. (Not to scale.)

Fig. 2. SEM picture of cross-section view of the device fabricated by epi-seal encapsulation process. The polysilicon cap layer creates a hermetically sealed enclosure. The pressure in the cavity is determined to be less than 1.5 Pa [17].
ber was maintained within $\pm 0.1^\circ$C range which corresponds to frequency uncertainty of $\pm 2.7$ ppm for design A resonators and $\pm 3.3$ ppm design B resonators respectively based on their TCF values. In addition, due to limitation of current setup capability, the measurement has additional error range of $\pm 0.4$ ppm. Based on this information, total error range is $\pm 3.1$ ppm and $\pm 3.7$ ppm for design A resonators and design B resonators, respectively. The main characteristics of design A resonators and design B resonators are summarized in Table 1.

### Table 1

| Main characteristics of MEMS resonators used for the resonant frequency stability test |
|----------------------------------|----------------|----------------|
| Resonator design                | Design A       | Design B       |
| Resonant frequency (kHz)        | $\sim 155$     | $\sim 129$     |
| Quality factor                  | $\sim 30,000$  | $\sim 50,000$  |
| TCF (ppm/°C)                    | $\sim 27$      | $\sim 33$      |
| Measurement uncertainty (ppm)   | $\sim 3.1$     | $\sim 3.7$     |

### 3. Long-term stability at constant temperature

The measurement setup diagram is shown in Fig. 4. Long-term frequency drift of these MEMS resonators was examined by monitoring six separate resonators. Each resonator was excited and measured approximately every 30 min for more than 1 year (about 10,000 h) using an Agilent 4395A network analyzer. To minimize temperature-related frequency variations, the resonators were installed in a temperature-controlled chamber, which provides test temperature within $\pm 0.1^\circ$C error range.

Fig. 5 represents monitored resonant frequency of MEMS resonators. The discontinuities in the data represent periods when the test was stopped for maintenance or improvement. As shown in the figure, the resonant frequency of all six resonators has total drift less than measurement error. Some instability of the resonant frequency during the first 500 h of operation can be seen. It is important to note that all four resonators present at the beginning of the study showed a similar initial frequency variation, where as the two resonators added after 3000 h did not. Our conclusion for this is, there is no actual drift in resonator characteristics, except for that due to initial instabilities in the measurement setup during first 500 h. The potential absence of “burn-in” drift in these resonators is an important advantage over quartz resonators, which typically drift by as much as 10 ppm during the first days or weeks of operation [20].
Fig. 5. Plot of resonant frequency vs. time for the resonators used in the long-term aging test. The top three are design A resonators and the next three are design B resonators. During 10,000 h operation, no trend of resonant frequency shift could be detected. Drift in resonant frequency is only within measurement error range, which is limited by instability of experimental temperature and resolution of network analyzer. The measured temperature data of the oven containing the resonators is given at the bottom. The discontinuities in the data represent periods when the test was stopped for maintenance or improvement.

To show more detail, an expanded plot of the first resonator is shown in Fig. 6. In this figure, we can see that the resonant frequency for both of resonators remained in error ranges, ±3.1 ppm and ±3.7 ppm for design A resonators and design B resonators, respectively. This was true for all the resonators monitored in this experiment.

4. Stability during and after temperature cycle

Another experiment was performed to examine resonant frequency stability after environmental temperature cycles. If there is axial stress on the resonator beam due to differential thermal expansion of the layers, it can cause change in resonant

Fig. 6. Plot of resonant frequency vs. time for one of design A resonators and design B resonators. Except for a few outliers, resonant frequency is maintained within less than ±3.1 ppm and ±3.7 ppm, respectively, which are expected maximum measurement error of design A resonators and design B resonators.
Fig. 7. (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 min 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. This result suggests long-term stability of resonant frequency even after large number of wide temperature cycles.

frequencies of MEMS resonators [21] 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 encapsulation.

The resonant frequency of two installed design A resonators was measured in between each temperature cycle for almost 700 cycles from −50 °C to +80 °C (Fig. 7a). The temperature inside the chamber ramped up to 80 °C and down back to 30 °C. After this cycle, temperature was held for 30 min to reach thermal equilibrium in the chamber. Then, the resonant frequencies of all the MEMS resonators were measured. The temperature was then ramped down to −50 °C, back to 30 °C, and the frequencies were measured again.

Almost 700 temperature cycles have been performed, and all the measurements were performed at 30 ± 0.1 °C. Again, the observed drift in resonant frequency was within measurement error range (Fig. 7b). In addition, the resonant frequency difference between measurements after high temperature cycles and after low temperature cycles stayed within the measurement error. The observed frequency shift is most likely related to slight temperature gradients within the apparatus at the time of the measurements.

5. Hysteresis of resonant frequency

The next experiment measured resonant frequency every 10 °C while the temperature was ramping up and down between −10 °C and +80 °C. Again, design A resonator was used in this experiment. The temperature in the chamber was increased in steps of 10 °C, and at each step the chamber was held for 30 min and allowed to reach thermal equilibrium before the resonant frequency was measured. The same process was repeated for decreasing temperature from +80 °C to −10 °C. As shown in Fig. 8, no trend between temperature increasing and decreasing cases has been found and the difference in resonant frequency was again within measurement error range.

The results from these separate experiments indicates that there is no significant residual stress or hysteresis, which might affect resonant frequency stability for changes in environmental temperature.

This is the first set of experiments on MEMS resonators sealed in a clean high-temperature process (950°C epitaxial polysilicon deposition), and this is also the first time MEMS resonators have displayed long-term stability in the few ppm ranges for constant temperature tests and temperature cycle tests. In most other respects, these resonators are no
of self-oscillating circuits, these resonators will operate continuously at their resonant frequencies, allowing investigation of resonant frequency stability related to material fatigue or aging. We plan to build a new test set-up which will provide a more stable operating temperature to further refine stability measurement of MEMS resonators.

Acknowledgements

This work was supported by DARPA HERMIT (ONR N66001-03-1-8942), Bosch Palo Alto Research and Technology Center, a CIS Seed grant, The National Nanofabrication Users Network facilities funded by the National Science Foundation under award ECS-9731294, and The National Science Foundation Instrumentation for Materials Research Program (DMR 9504099). The authors would especially like to thank Gary Yama (Robert Bosch Corporation), Markus Lutz (Robert Bosch Corporation, currently at SiTime), and Aaron Partridge (Robert Bosch Corporation, currently at SiTime) for their guidance and assistance, without whom this work would not have been possible. We would also like to thank John R. Vig from the U.S. Army Communications Electronics Command for his valuable advice.

References


Fig. 8. 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. No trend between temperature increasing and decreasing cases has been found.

different than resonators tested elsewhere by other groups, in a variety of lower-temperature packages. We believe that the high-temperature, clean epi-polysilicon process creates an environment without trapped molecules capable of absorbing on the resonator, and without oxygen and other molecules capable of chemically bonding to the resonator. The dominant residual gas is hydrogen, which is incapable of bonding to the silicon surfaces at these operating temperatures. All other encapsulated species are probably absorbed permanently on the walls of the silicon encapsulation during the high-temperature encapsulation process. The absence of chemically active molecules free in the chamber prevents frequency changes due to the added mass of these molecular species, revealing the underlying stability of silicon as a resonator material.

6. Conclusions

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

This improved performance is attributed to the clean, high-temperature fabrication process used to hermetically encapsulate these resonators. Our encapsulation process is able to provide an effective shield for resonant frequency stability for MEMS resonators. This suggests that underlying stability of the silicon MEMS resonators at given temperature should be good enough for commercial application, and the drift and hysteresis problems observed in other MEMS resonators have never been fundamental, but rather have always been due to their operating environment. Furthermore, this justifies the effort development of temperature compensation methods to overcome temperature coefficient of frequency (TCf) 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, allowing investigation of resonant frequency stability related to material fatigue or aging.

Biographies

Bongsang Kim received the BS degree in mechanical design and production engineering from Seoul National University, Seoul, Korea, and the MS degree in mechanical engineering from Stanford University in 2004. He is currently working toward the PhD degree in the department of mechanical engineering at Stanford University. From 1998 to 2001, he was working at Hyundai Mobis as a mechanical engineer, and in 2005, he has interned at Agilent Labs in Palo Alto, CA, on development of nano-stepper for AFM application. His research interests include reliability of MEMS structures, MEMS packaging, material diffusion, and energy loss and stability of micromechanical resonators.

Rob N. Candler received the BS degree in electrical engineering from Auburn University in 2000 and the MS and PhD degrees in electrical engineering from Stanford University in 2002 and 2006, respectively. He is currently a research engineer at Robert Bosch Research and Technology Center, Palo Alto, CA. His research interests include energy loss mechanisms in micromechanical resonators, MEMS packaging, and the impact of surface phenomena on MEMS sensors.

Matthew A. Hopcroft received the BSc in computer engineering from The George Washington University, Washington, DC, in 1998, and the MPhil degree in engineering from Cambridge University, Cambridge, UK, in 2002. He is currently working toward the PhD degree in the Department of Mechanical Engineering at Stanford University, Stanford, CA. His research interests include MEMS material property measurements, microsystem thermal design, and micromechanical resonators.

Manu Agarwal received his BTech degree in electrical engineering from the Indian Institute of Technology Kanpur, India, in 2003 and MS degree in electrical engineering from Stanford University, Stanford, CA, USA in 2005. He is currently working towards a PhD degree in electrical engineering at Stanford University. During his undergraduate career he interned at the Technical University of Ilmenau in Germany and at the EPFL, Lausanne, Switzerland. During his graduate career, he has interned at Agilent Labs in Palo Alto, CA, on characterizing dipole surface drive MEMS actuators. His current research interests include design of high frequency MEMS resonators for frequency references and in characterization of the nonlinearity and on studying phase noise in electrostatic MEMS resonators.

Woo-Tae Park received the BS degree in mechanical design from Sungkyunkwan University, Seoul, Korea, in 2000, the MS and PhD degrees in mechanical engineering from Stanford University, Stanford, CA, in 2002 and 2006, respectively. He has been working on optical measurements for electrical contact deformation, wafer scale encapsulated MEMS devices, and submillimeter piezoresistive accelerometers for biomedical applications. His current interest lies in high volume silicon manufacturing, especially wafer level packaged micromechanical components used with integrated circuits. Dr. Park is currently a packaging engineer at Intel, Chandler Arizona. Dr. Park authored five journal papers and thirteen conference papers.

Thomas W. Kenny received the BS degree in physics from the University of Minnesota, Minneapolis, in 1983, and the MS and PhD degrees in physics from the University of California, Berkeley, in 1987 and 1989, respectively. From 1989 to 1993, he worked at the NASA Jet Propulsion Laboratory, where his research focused on the development of electron-tunneling high-resolution microsensors. In 1994, he joined the Mechanical Engineering Department, Stanford University, Stanford, CA, and directs MEMS-based research in a variety of areas including resonators, wafer-scale packaging, cantilever beam force sensors, microfluidics, and novel fabrication techniques for micromechanical structures. Professor Kenny is a founder and CTO of Cooligy, a microfluidics chip cooling components manufacturer, and founder and board member of SiTime, a developer of CMOS timing references using MEMS resonators. He is presently the Stanford Bosch Faculty Development Scholar and the General Chairman of the 2006 Hilton Head Solid State Sensor, Actuator, and Microsystems Workshop. Professor Kenny has authored and co-authored over 200 scientific papers and holds 40 patents.