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Design of Temperature Sensitive Structure for Micromechanical Silicon Resonant Accelerometer

Heng Li, Libin Huang* , Qinqin Ran
School of Instrument Science and Engineering, Southeast University
Nanjing, China
E-mail: 1113762274@qq.com
*101010566@seu.edu.cn

Songli Wang
Aviation Key Laboratory of Science and Technology on Inertia, FACRI
Xi'an, China
E-mail: 618gdb104@facri.com

***Abstract*—A micromechanical silicon resonant accelerometer (MSRA) is a potential micro accelerometer with high accuracy. One of the most important factors affecting its performance is temperature. To research the effect of temperature on micromechanical silicon resonant accelerometer, this study based on the original micromechanical silicon resonant accelerometer, designs a chip-level temperature-sensitive structure which a pair of temperature resonators is arranged on both sides of the force resonator of the original accelerometer to ensure symmetry of the MSRA, as well as compares and selects the appropriate structure, fundamental frequency, and size. The ANSYS simulation is used to verify the rationality of the structure design. The MSRA is fabricated using the Deep Dry Silicon on Glass technique and packaged in metal shell, a measurement circuit is designed and a full temperature test is conducted. The results show that the resonant frequency of the temperature resonator is strongly sensitive to temperature changes but not sensitive to acceleration, and that it can reflects temperature change in the package cavity. Therefore, the temperature resonator can achieve accurate temperature measurement of accelerometer and can be used in temperature compensation.**

Keywords-Accelerometer; MEMS; Resonant; Temperature error; Temperature measurement structure

I. INTRODUCTION

A micromechanical silicon resonant accelerometer (MSRA) with high sensitivity and resolution has frequency as its output signal, as well as the advantages of wide dynamic range, anti-interference ability, and high stability. Given its significant advantages and high-precision measurement, it has become one of the most popular high-precision Micro Electro-Mechanical Systems [1-4]. The publicly reported MSRA with the highest performance, has a scale factor stability of 0.14 ppm and a bias stability of 0.19μg, was developed by the Draper laboratory [2]. Hyeon Cheol Kim from Seoul National University designed inertial-grade vertical-and lateral-types of differential accelerometers. The out-of-plane resonant accelerometer shows a bias stability of 2.5μg, a scale factor of 70 Hz/g, and a bandwidth of 100Hz. The in-plane resonant accelerometer indicates a bias stability of 5.2μg, a scale factor of 128Hz/g and a bandwidth of 110Hz [3]. Lin He and Yong Ping Xu from the National University of Singapore developed an MSRA with a bias stability of 5μg, a scale factor stability of 3 ppm, and a scale factor of 100Hz/g [5].

Temperature is one of the most important factors affecting MSRA performance, and temperature compensation is commonly used to suppress temperature error. References [6-9] proposed different temperature compensation methods, have made some compensation effect. To achieve temperature compensation, the first step is to measure the temperature of the MSRA. The traditional method generally measures the temperature outside the MSRA; however, this method is affected by the temperature gradient and temperature delay, and exists a large error to accurately reflect temperature changes. Guoming Xia proposed an MSRA with an integrated temperature measurement structure [10]. Fan Wang established a platinum resistance on the MSRA glass substrate to measure temperature [11]. Both designs are available for the real-time temperature measurement of MSRA.

This study designed a chip-level temperature sensitive structure based on the original MSRA structure and it can achieve the real-time temperature measurement of MSRA.

II. DESIGN OF TEMPERATURE RESONATOR STRUCTURE

A. Fundamental Frequency of Temperature Resonator Structure

Both force resonator and temperature resonator exist in the MSRA with temperature sensitive structure. A coupling exists between two resonators if their frequencies are identical. To eliminate or decrease the coupling, a large frequency difference between the force and temperature resonators can be designed so that the operating frequencies of the two do not coincide with their respective operating ranges. A MSRA without a temperature-sensitive structure is shown in Fig .1. The MSRA consists of proof mass, leverage, and support system, as well as stress-sensitive resonators. Two identical double-ended tuning forks (DETFs) are symmetrically arranged and connected by the proof mass, which converts the acceleration into an inertial force magnified by leverage. One resonator's frequency will increase under the tensile force, whereas the other will decrease under the compressive force. The acceleration will be calculated from the frequency difference between the two resonators. Table I shows the resonant frequency of the upper and lower force resonators at axial accelerations utilizing ANSYS.

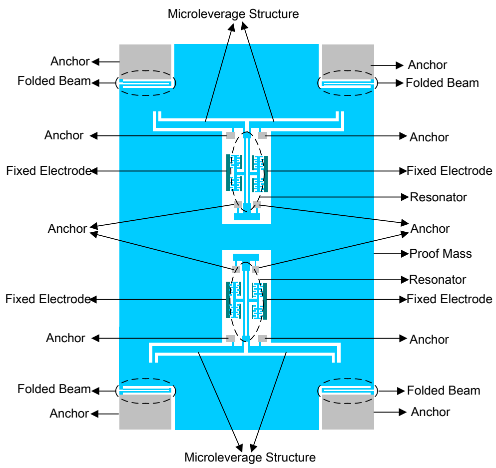


Figure 1. A MSRA without temperature sensitive structure

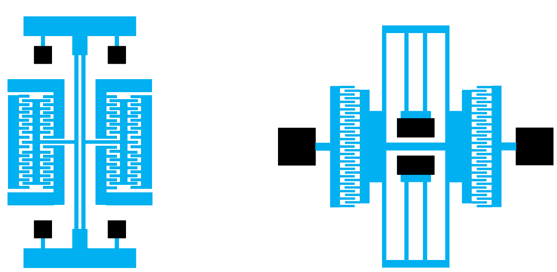
TABLE I. RESONANT FREQUENCY OF FORCE RESONATOR AT AXIAL ACCELERATIONS

Acceleration [g]	Frequency of force resonator 1 [Hz]	Frequency of force resonator 2 [Hz]
20	27,646	30,702
10	28,439	29,972
0	29,208	29,233
-10	29,957	28,453
-20	30,687	27,661

Table I shows that the resonant frequency range of the temperature resonator should be either less than 27,646 Hz or more than 30,702 Hz.

B. Comparison of Temperature Resonator Structure

As Fig .2 shows, micro electrostatic silicon resonator has two main forms: tuning fork (Fig .2a) and folding beam (Fig .2b).



(a) Tuning fork (b) Folding beam

Figure 2. Vibration beam structure forms of temperature resonator

Considering process limitation, the thickness of the temperature resonator is 80μm and the width is 10μm, and the length of the vibration beam is 1400μm and the distance is 20μm. With the same size of vibration beam, a comparative analysis of resonant frequency at different temperatures is performed on the tuning fork and folding beam resonators as shown in Table II.

TABLE II. RESONATOR FREQUENCY OF TUNING FORK AND FOLDING BEAM AT DIFFERENT TEMPERATURES

Temperature [℃]	Frequency of tuning fork resonator [Hz]	Frequency of folding beam resonator [Hz]
60	29,531	16,660
40	29,402	16,670
20	29,086	16,680
0	28,527	16,690
-20	27,653	16,700
-40	26,365	16,710

Table II indicates that the tuning fork resonator is more sensitive to temperature changes. Improving the scale factor can reduce the difficulty of signal detection. Therefore, the use of tuning fork resonators as temperature resonators to measure temperature changes in MSRA is more appropriate.

C. Design of a MSRA with Temperature Sensitive Structure

In Fig .3, a pair of temperature resonators is arranged on both sides of the force resonator to ensure symmetry of the MSRA. The resonant beams of temperature resonators are parallel to the resonant beams of force resonators.

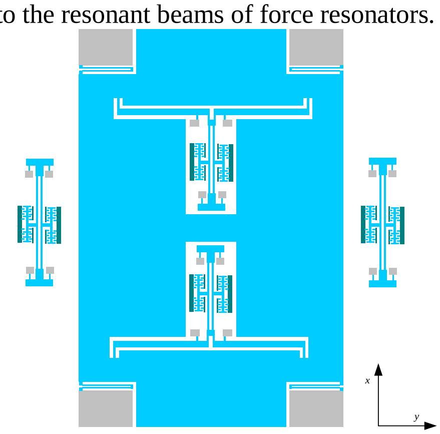
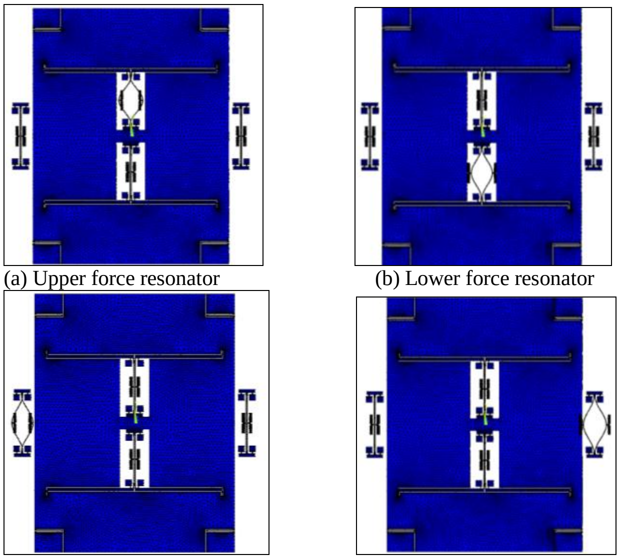


Figure 3. MSRA with Temperature Sensitive Structure

FINITE ELEMENT ANALYSIS OF TEMPERATURE RESONATOR STRUCTURE

A. Working Modes Analysis

ANSYS is used to perform the mode analysis on the MSRA with temperature resonator. The working modes of the resonators are shown in Fig .4. From the finite element method, the resonant frequency of the upper and lower force resonators is 29,223 and 29,210 Hz, respectively; whereas the resonant frequency of the left and right temperature resonators is 22,740 and 22,739Hz, respectively. Owing to the accumulated errors of ANSYS, a slight difference in fundamental frequency exists between the upper and lower force resonators and between the left and right temperature resonators.



(a) Upper force resonator (b) Lower force resonator

(c) Left force resonator (d) Right force resonator

Figure 4. The working modes of the resonators of MSRA with temperature resonator

B. *Thermal Simulation*

Thermal simulation is implemented by ANSYS software and the relationship between the temperature and the resonant frequency is shown in Table III.

TABLE III. THE RELATIONSHIP BETWEEN TEMPERATURE AND THE RESONANT FREQUENCY

Temperature [℃]	Resonant frequency [Hz]
-40	21,634
-30	21,887
-20	22,138
-10	22,385
0	22,629
10	22,871
20	23,111
30	23,348
40	23,582
50	23,814
60	24,044

According to Table III, the maximum operating frequency at 24,044 Hz is less than the minimum operating frequency of the force resonator (27,646 Hz), so that the structural parameters of the temperature resonator are reasonable.

C. *Effect of Acceleration on Resonant Frequency of the Temperature Resonator*

The force resonator is sensitive to acceleration and temperature; however, as a temperature sensitive element, the temperature resonator should be sensitive to temperature but not to acceleration. The use of ANSYS to apply different accelerations under the three axis on the MSRA and the effect of acceleration on the temperature resonator are shown in Table IV-Table VI.

According to Table IV, Table V and Table VI, the temperature resonator is insensitive to acceleration, making the temperature resonator suitable to be used as a temperature-sensitive element to measure MSRA temperature.

TABLE IV. X-AXIAL ACCELERATION ON TEMPERATURE RESONATOR

Acceleration [g]	**Frequency under x-axial acceleration [Hz]**	
	Left resonator	***Right resonator***
20	22,739.802,9	22,736.207,1
10	22,739.798,5	22,736.212,6
0	22,739.795,2	22,736.219,1
-10	22,739.792,9	22,736.226,5
-20	22,739.791,5	22,736.235,0

TABLE V. Y-AXIAL ACCELERATION ON TEMPERATURE RESONATOR

Acceleration [g]	**Frequency under y-axial acceleration [Hz]**	
	Left resonator	***Right resonator***
20	22,739.985,5	22,738.939,2
10	22,739.985,5	22,738.939,2
0	22,739.795,2	22,738.219,1
-10	22,739.985,5	22,738.939,0
-20	22,739.985,5	22,738.939,0

TABLE VI. Z-AXIAL ACCELERATION ON TEMPERATURE RESONATOR

Acceleration [g]	**Frequency under z-axial acceleration [Hz]**	
	Left resonator	***Right resonator***
20	22,739.796,4	22,736.220,2
10	22,739.796,4	22,736.220,2
0	22,739.795,2	22,736.219,1
-10	22,739.794,6	22,736.218,5
-20	22,739.794,0	22,736.217,9

III. FABRICATION AND PACKAGING

The MSRA is fabricated using the Deep Dry Silicon On Glass (DDSOG) technique. Silicon and glass are the structural layout and the substrate of the MEMS device, respectively. Silicon-glass bonding process is used to combine the silicon mass and glass substrate. The main process is: (a) Etching the bonding area on silicon wafer. (b) Depositing the metal electrodes on glass substrate. (c) Bonding the glass substrate to silicon wafer. (d) Thinning and polishing on silicon wafer. (e) Deep reactive-ion etching through silicon wafer to release the structure. A small structural stress is generated because of the use of monocrystalline silicon as a structural material; and the gap between the silicon structure and the glass substrate is sufficiently large, resulting in minimal parasitic capacitance. In addition, DDSOG can achieve metal deposition and processing to the metal wire product. Fig .5 shows the local structure of the improved temperature resonator under the 3D video microscope.

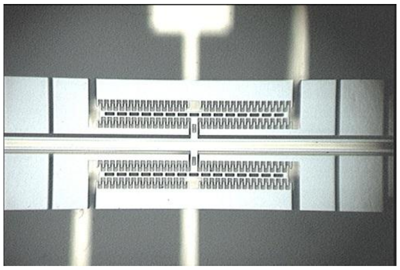


Figure 5. The local structure of the temperature resonator under the 3D video microscope

Accelerometer structure is packaged in metal shell. In the atmosphere the damping of resonator is so large that it should affect oscillation of resonator. The vacuum encapsulation of the MSRA is implemented.

IV. EXPERIMENT

Control and Detection Circuit of Temperature Resonator

Fig .6 shows that the circuit of the temperature resonator mainly includes the analog driving and digital frequency measurement sections. The analog driving section is comprised of the interface circuit, phase, and amplitude control circuit. The phase control circuit is implemented by an analog phase-locked loop used to suppress noise. On the one hand, the output signal is for driving the resonator vibration. On the other hand, for field-programmable gate array (FPGA) measures the instantaneous frequency. Amplitude control circuit utilizes the direct-current automatic generation control circuit to extract the amplitude signal from the interface circuit output signal, and compares it with the reference voltage. Afterwards, the amplitude control signal, through the adder, controls the amplitude of the drive signal to achieve steady oscillation at the resonant frequency. The digital frequency measurement section is mainly implemented by the digital circuit. Frequency measurement algorithm is written in FPGA, so that the output frequency signal of the phase-locked loop can be measured on time. The measurement results are transmitted via the universal asynchronous receiver/transmitter to the PC for display and recording. Figs .7 and 8 show the driving circuit board and the frequency measurement module with the same shape and size, respectively.

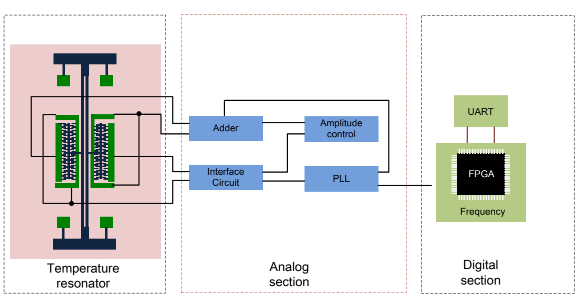


Figure 6. The control and detection circuit of temperature resonator

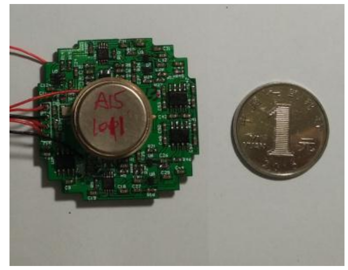


Figure 7. The structure and driving circuit

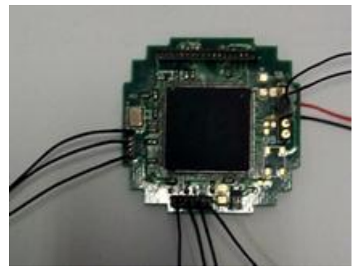


Figure 8. The frequency measurment module

Full Temperature Experiment

The accelerometer operates from -40 ℃ to 60 ℃. To verify the effect of the temperature sensitive structure, the accelerometer is placed in the temperature control box. The variable temperature range in the temperature control box is from −60 °C to 100 °C, and the temperature control accuracy is 0.1 ℃. The experiment procedure is as follows:

1) Energize the temperature resonator but not the force resonator;

2) Decrease the temperature to −40 ℃ and keep the temperature for 120 min;

3) When the temperature resonator output is stable, use a 1 Hz sampling frequency to record the result in 30 s and calculate the average as the temperature resonator output at the point of the current temperature;

4) Increase the temperature to −20 ℃ and keep the temperature for 120 min;

5) When the temperature resonator output is stable, use 1 Hz sampling frequency to record the result in 30 s, and calculate the average as the temperature resonator output at the point of the current temperature;

6) Increase the temperature to 0 ℃ and keep the temperature for 120 min;

7) When the temperature resonator output is stable, use 1 Hz sampling frequency to record the result in 30 s, and calculate the average as the temperature resonator output at the point of the current temperature;

8) Increase the temperature to 20 ℃ and keep the temperature for 120 min;

9) When the temperature resonator output is stable, use 1 Hz sampling frequency to record the result in 30s, and calculate the average as the temperature resonator output at the point of the current temperature;

10) Increase the temperature to 40℃ and keep the temperature for 120 min;

11) When the temperature resonator output is stable, use 1 Hz sampling frequency to record the result in 30s, and calculate the average as the temperature resonator output at the point of the current temperature;

12) Increase the temperature to 60℃ and keep the temperature for 120 min;

13) When the temperature resonator output is stable, use 1 Hz sampling frequency to record the result in 30s, and calculate the average as the temperature resonator output at the point of the current temperature;

After processing the data, we obtain the values of the full temperature points of the temperature resonator, as shown in Table VII.

TABLE VII. THE EXPERIMENT RESULTS UNDER FULL TEMPERATURE OF TEMPERATURE RESONATOR

Temperature [℃]	**Resonant frequency [Hz]**
60	27,975.343,43
40	27,078.624,69
20	26,049.472,18
0	25,097.384,74
20	23,841.168,93
-40	23,080.606,04

According to Table VII, the fundamental frequency of the temperature resonator is greater than the design value, which is mainly affected by the processing errors and the packaging stress. The frequency of the temperature resonator changed significantly with the temperature changes. Furthermore, the trend is monotonic, which means that the temperature resonator frequency reflects the temperature changes.

V. CONCLUSION

To solve the serious problem of temperature effect on the output frequency of MSRA, we based the study on the original MSRA and designed a chip-level temperature-sensitive structure. The temperature resonator is strongly sensitive to temperature changes but not sensitive to acceleration. Therefore, the temperature resonator can realize the real-time temperature measurement of MSRA and can be used in temperature compensation.

VI. ACKNOWLEDGMENT

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