Long-term Stability Enabling Technology of Silicon-Based Piezoresistive MEMS Pressure Sensor

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Abstract. Silicon-based piezoresistive microelectromechanical systems (MEMS) pressure sensor is one of the best studied and commercialized devices among all MEMS devices due to simple structure, easy reading circuit, strong batch fabrication capability and low price. The biggest technical bottleneck of this sensor for high-end applications such as aerospace is long-term stability after packaging. Therefore, long-term stability improvement technologies, as the common key technologies, have been widely concerned by academia and industry. In this paper, three common enabling technologies including pulsating fatigue, thermal-cold cycling and vibration aging are adopted to evaluate the effect of long-term stability of silicon-based piezoresistive MEMS pressure sensors by using control variable method and orthogonal test (OT) method. The comparative test results indicate that all these three technologies can improve the long-term stability of the pressure sensor. In addition, an optimized combination of environmental stress parameters is found to improve the stability more than 90% higher than before the test. The long-term stability of the sensors through the optimal parameter combination aging method is better than the original factory method. The research results can be used for reference to improve the long-term stability of various silicon-based pressure sensors.

1. Introduction
Silicon-based piezoresistive MEMS pressure sensor is one of the best studied and commercialized devices among all MEMS devices due to simple structure, easy reading circuit, strong batch fabrication capability and low price [1-2], which has been widely used in many fields such as automotive, medical, consumer electronics, industry, aviation, aerospace, biomedical engineering and so on [3]. Long-term stability is one of the most significant parameters to evaluate the sensor characteristics that determine the validity and accuracy of a pressure sensor [4]. Therefore, long-term stability improvement technologies, as the common key technologies, have been widely concerned by academia and industry.

Long-term stability of piezoresistive MEMS pressure sensors is generally related to materials, manufacturing processes and operating environments [5]. A lot of researchers have made many beneficial explorations in improving the long-term stability of sensors, which can be summarized into the following four aspects. The first is to select the most suitable sensitive materials and enable their fabrication process direct integration of MEMS sensors [6-7]. For example, materials with high strength limitation and elastic limitation, effective elastic modulus temperature stability, small elastic hysteresis, small mechanical and heat treatment residual stress should be selected for pressure-bearing diaphragm and body beam. The second is to eliminate residual stress, which is mainly achieved by heat treatment and mechanical method [5, 8-13]. Heat treatment method can eliminate residual stress
because the piezoresistive coefficient of sensitive piezoresistive materials is susceptible to temperature [11]. Mechanical methods mainly use stress repeated or random loading to eliminate residual stress. The third is to improve the fabrication and assembly process of the sensor [14]. In order to improve the symmetry and uniformity of the structure and materials, processing error should be controlled strictly during the process. The last is to use data processing technology to compensate and correct quantifiable stability errors. However, the randomness of stability errors causes the uncertainty in practical application.

As mentioned above, it is an effective method to improve the long-term stability of piezoresistive MEMS pressure sensors that eliminating residual stress and stress concentration. Stress relief methods such as heat treatment, repeated loading and mechanical vibration have been proven to be feasible. However, there is still a lack of systematic research and optimization analysis of environmental stress parameters for practical applications. In this paper, three common enabling technologies including pulsating fatigue, thermal-cold cycling and vibration aging are adopted to evaluate the effect of long-term stability of silicon-based piezoresistive MEMS pressure sensors by using control variable method and OT method.

2. Methods and Experimental Design

2.1. Experimental process
This paper takes several silicon-based piezoresistive MEMS pressure sensors of the same batch without aging test as the research objects. Pulsating fatigue OT, thermal-cold cycling OT and vibration aging OT were performed in parallel. The static calibration and rated point stability test were carried out before and after the OT. The stability data of rated point before and after the OT was compared and the effect of different stability enabling technology was analyzed. Finally, the sensors using the optimal parameter combination equivalent accelerated aging method and the original factory aging test method sensor were compared for long-term stability monitoring at the rated point.

2.2. OT design

![OT load curves](image)

Figure 1. OT load curves: (a) Pulsating fatigue load curve, (b) Thermal-cold cycling load curve, (c) Random vibration load curve.

2.2.1. Pulsating fatigue OT
The pulsating fatigue pressure loads on the sensitive component and affects the creep of the sensitive materials, which can effectively release the residual stress introduced by bonding [5]. The stress and strain of the pressure sensitive structure are affected by upper pressure limit. The effective release of residual stress is determined by the loading time. Due to the residual stress is eliminated slowly, it requires multiple pressure loading cycles. Pulsating fatigue load curve is shown in Figure 1(a). Thermal-cold cycling OT.

$L_9(3^4)$ horizontal orthogonal table is adopted to design the test, upper limit of pressure amplitude $(P)$, load-time $(T_p)$ and loading cycles $(N_p)$ are selected as OT factors to study the influence of pulsating fatigue test parameters on the stability of silicon-based piezoresistive MEMS pressure sensor and obtain the optimal combination of parameters. The lower limit of pressure amplitude is 1/2 of the full
scale of the sensor (200 kPa). The upper limit is set to 100%, 120%, and 150% of the full-scale load. The load-time is set to 0.5s, 1s, 5s. Loading cycles is set to 1000 times, 5000 times, and 10000 times, pulsating fatigue OT parameters are shown in Table 1. According to the general principle of OT design, empty column is mainly used to estimate the random error of experiment.

Table 1. Pulsating fatigue OT parameters table.

| NO. | P(kPa) | T_p(s) | N_p |
|-----|--------|--------|-----|
| 1   | 200    | 0.5    | 1000|
| 2   | 200    | 1      | 5000|
| 3   | 200    | 3      | 10000|
| 4   | 240    | 1      | 10000|
| 5   | 240    | 2      | 10000|
| 6   | 240    | 3      | 5000 |
| 7   | 300    | 1      | 5000 |
| 8   | 300    | 2      | 10000|
| 9   | 300    | 3      | 1000 |

2.2.2. Vibration aging OT

Thermal-cold cycling can be utilized as an acceleration factor for failure mechanisms such as creep and plastic deformation of materials [15]. Along with the increasing of temperature, the thermal motion energy of atoms increases and the lattice distortion decreases or disappears. The atomic thermal motion is greater, the residual stress release is more favorable [5]. Thermal-cold cycling load curve is illustrated in Figure 1(b). Increasing the rate of temperature change is instrumental in stimulating latent flaws. Load-time and loading cycles are related to product life. Excessive loading time will introduce new stresses, too many loads will shorten the service life.

Table 2. Thermal-cold cycling OT parameters table.

| NO. | R(℃/min) | T_R(h) | N_R |
|-----|-----------|--------|-----|
| 1   | 5         | 1      | 5   |
| 2   | 5         | 2      | 10  |
| 3   | 5         | 3      | 20  |
| 4   | 10        | 1      | 0.5 | 20  |
| 5   | 10        | 2      | 1   | 5   |
| 6   | 10        | 3      | 0.1 | 10  |
| 7   | 15        | 1      | 1   | 10  |
| 8   | 15        | 2      | 0.1 | 20  |
| 9   | 15        | 3      | 0.5 | 5   |

Temperature changing rate (R), load-time (T_R) and loading cycles (N_R) are selected as the factors of thermal-cold cycling OT, and the L_9(3^4) horizontal orthogonal table arrangement test is adopted. Temperature changing rate is set to the limit capability value and the intermediate value of the test equipment, taking 5℃/min, 10℃/min, and 15℃/min; The upper and lower limits of the temperature amplitude are selected as the temperature limit values of the test samples (-40℃~85℃), and load-time is taken as 0.1h, 0.5h, and 1h respectively. Loading cycles is 5, 10, and 20 times according to the production experience. Thermal-cold cycling OT parameters is shown in Table 2.

2.2.3. Vibration aging OT

The basic theories of vibration aging test mainly include plastic deformation, fatigue, lattice dislocation slip and other theoretical viewpoints [5], but the specific mechanism of action is still inconclusive. The mechanical force generated by the vibration aging method acts on all parts of the sensor, elimination of the residual stress and stress concentration introduced during the fabrication process. The amplitude of the vibration generates transient stress and strain inside the sensor under test,
the natural frequency of each position of the sensor is different, so the random vibration frequency mode is usually used in the loading test. Short vibration loading time will affect the effect of stability improvement. In contrast, too long will affect the service life. The random loading vibration curve is shown in Figure 1(c).

Vibration amplitude (A), vibration frequency (f) and load-time (TA) are selected as the factors of the OT of the vibration aging, and the L9(3⁴) horizontal orthogonal table arrangement test is adopted. The amplitude of the vibration force is set as the ultimate vibration force value and the intermediate value of the vibration test equipment, 1g RMS, 5g RMS, and 10g RMS are taken as the factor level; the upper limit of the loading frequency is set to the upper limit value, the intermediate value and the lower value of the random frequency of the vibration test equipment, so the random vibration frequency range is taken as the factor level of 20~100Hz, 20~1000Hz, and 20~2000Hz; Load-time is based on production experience, taking 0.5h, 5h, and 10h. Vibration aging OT parameters is shown in Table 3.

Table 3. Vibration aging OT parameters table.

| NO. | A(g RMS) | f(Hz)  | TA(h) |
|-----|----------|--------|-------|
| 1   | 1        | 20-100 | 0.5   |
| 2   | 1        | 20-1000| 5     |
| 3   | 1        | 20-2000| 10    |
| 4   | 10       | 20-1000| 10    |
| 5   | 10       | 20-2000| 0.5   |
| 6   | 10       | 20-100 | 5     |
| 7   | 5        | 20-2000| 5     |
| 8   | 5        | 20-1000| 10    |
| 9   | 5        | 20-1000| 0.5   |

2.3. Data characterization of test results
Pre-processing of the static calibration and rated point stability test data according to calculation method of performance index of appendix A of GB 15478-2015[16]. The least squares linear equation is used for the working characteristic equation, rated point stability calculation reference zero-point stability calculation method, ΔY is the difference between the actual output value and the characteristic equation value under 100 kPa pressure.

In order to evaluate long-term stability enabling effects of the three enabling technologies, the stability data of rated points are comprehensively investigated by three evaluation indexes: stabilization time Δt, volatility Δe and stability change Δy. Stabilization time reflects the speed of the sensor to reach a relatively stable value; volatility reflects the output steady-state error of the sensor, and stability change reflects the output stability of the sensor, the schematic definition is illustrated in the Figure 2.

![Figure 2. OT stability data processing diagram.](image-url)
3. Results and Discussion

The static calibration and rated point stability test of the pressure sensor before and after the OT are based on the national standard GB/T 15478-2015 pressure sensor performance test method [16]. Experimental set-up for pressure sensor calibration testing is shown in Figure 3, and the whole measurement system is composed of standard pressure source system (pneumatic piston gauge, accuracy class 0.005%), temperature chamber (ETH-408-60-CP-AR, temperature -40°C~100°C, humidity 0~98%RH), DC power (E3634A) and reading device (E34972A), all equipment performance meets national standards. Experimental set-up for OT is shown in Figure 4.

Firstly, evaluation index values of stabilization time, volatility and stability change obtained under test parameters in table 1, 2 and 3 are statistically calculated. The effect of three enabling technology on the stability evaluation index is shown in the box diagram of Figure 5, and the smaller number means more improvement. Statistical results demonstrate that a combination of factors that improve sensor stability of the three methods is present. The effect of the three methods for improvement of the stabilization time is equal, which can be shortened by about 80%. The improvement of stability volatility is obvious up to around 80% by using thermal-cold cycling and vibration aging method. Three methods have obvious effect on improving stability change, all of which exceed 90%.
Figure 5. Comparison of stability improvement effects of different Enabling technologies (Negative means improvement, positive means deterioration).

Secondly, the average value of the evaluation index corresponding to the same factor level is calculated. The factor level set corresponding to the maximum mean value is taken as the optimal parameter level combination. At last, mean value-range R is calculated, the larger R is, the greater influence of the corresponding factors on the evaluation index, and the more important the factors are to enhance the stability[17]. The optimal parameter level and range statistics of the three stability evaluation indexes improved by the three methods are presented in Table 4, 5 and 6, respectively. The optimal pressure amplitude of pulsating fatigue method to improve the evaluation index is 300 kPa, and loading cycles is 10000 times. Load-time of the stabilization time and the stability volatility is 0.5s, the optimal load time for only the stability change is 5s. In view of the fact that each factor is equivalent to the improvement of the stability change, the optimal parameter combination of this method is 300kPa pressure amplitude, 0.5s load-time and 10000 loading cycles.

Table 4. Optimum parameters and range statistics for stabilization time(Δt) improvement.

| Method          | Factor | optimum parameters | R   |
|-----------------|--------|--------------------|-----|
| Pulsating fatigue | P      | 300kPa             | 0.1198 |
|                 | T_p    | 0.5s               | 0.0947 |
|                 | N_p    | 10000times         | 0.0280 |
|                 | R      | 10℃/min            | 0.2290 |
| Thermal-cold cycling | T_R    | 0.5h               | 0.0923 |
|                 | N_R    | 5times             | 0.1070 |
|                 | A      | 1gRMS              | 0.0741 |
| Vibration aging | f      | 20-1000Hz          | 0.2024 |
|                 | T_A    | 10h                | 0.1107 |

Table 5. Optimum parameters and range statistics for volatility(Δe) improvement.

| Method          | Factor | optimum parameters | R   |
|-----------------|--------|--------------------|-----|
| Pulsating fatigue | P      | 300kPa             | 1.0630 |
|                 | T_p    | 5s                 | 0.6137 |
|                 | N_p    | 10000times         | 1.2372 |
|                 | R      | 15℃/min            | 0.1736 |
| Thermal-cold cycling | T_R    | 0.5h               | 0.1015 |
|                 | N_R    | 20times            | 0.0714 |
|                 | A      | 10gRMS             | 0.4288 |
| Vibration aging | f      | 20-1000Hz          | 0.3500 |
|                 | T_A    | 0.5h               | 0.1365 |
Table 6. Optimum parameters and range statistics for stability change($\Delta y$) improvement.

| Method                  | Factor | optimum parameters | $R$  |
|-------------------------|--------|--------------------|------|
| Pulsating fatigue      | $P$    | 300kPa             | 0.1726 |
|                         | $T_p$  | 0.5s               | 0.1798 |
|                         | $N_p$  | 10000 times        | 0.0550 |
|                         | $R$    | $15^\circ$C/min    | 0.3353 |
| Thermal-cold cycling    | $T_R$  | 0.5h               | 0.0474 |
|                         | $N_R$  | 20 times           | 0.2900 |
| Vibration aging         | $f$    | 20-2000Hz          | 0.0701 |
|                         | $T_A$  | 5h                 | 0.0305 |

As can be seen from Figure 5, the effect of thermal-cold cycling parameters in each group on the stability improvement evaluation index is equivalent. According to the statistical results of Table 4, 5 and 6, the optimal load-time of the method is 0.5h. The temperature change rate has the greatest influence on the stability improvement effect, therefore it can be set to 10-15$^\circ$C/min. 5 cycles is enough to shorten the stabilization time, while to improve the stability change and stability volatility, the number of cycles can be set to 20.

As shown in Figure 5, among these three comparison methods, the vibration aging method has the best effect on stability improvement. According to the statistical results of Table 4, 5 and 6, the improvement of the stability change of each factor level of the method can be maintained above 85%. Therefore, we only need to balance the stabilization time and volatility, the random vibration frequency range is determined to be 20~1000Hz. To effectively shorten the stabilization time, the vibration amplitude can be set to $1g_{RMS}$ and the load-time should be reached to 20h. To effectively improve the stability volatility, the load-time can be set to 0.5h and the vibration amplitude should be reached to $10g_{RMS}$.

To further study the effectiveness of our improved method, we performed an equivalent accelerated aging test on three same batch sensors using the optimal combination of parameters obtained previously. The aging test sequence is pulsating fatigue, vibration aging, and thermal-cold cycling. The stability of sensors using our aging method and original factor aging method were performed at a rated point of 100kPa and an ambient temperature of 20$^\circ$C for more than 70 days. The final comparison results are shown in Figure 6. The rated point stability of the sensors using our equivalent accelerated aging method are better than 0.04% FS, which is significantly improved compared to the sensors using the original factory aging method. It indicates that our method is an effective approach to improve the long-term stability.

![Figure 6. Comparison results of long-term stability between our method and the original factory method.](image-url)
4. Conclusions

In this paper, three indexes of stabilization time $\Delta t$, volatility $\Delta e$ and stability change $\Delta y$ were used to evaluate long-term stability enabling effects of three enabling technologies including thermal-cold cycling, pulsating fatigue and vibration aging. The experimental results show that all three aging processes can improve the long-term stability of silicon-based piezoresistive MEMS pressure sensor. The optimal factors and horizontal combination in improving the stability were obtained. Three methods are equally effective in improving the stabilization time of sensors and can be shortened by about 80%. Thermal-cold cycling and vibration aging method can achieve 80% improvement in sensor volatility, while the pulsating fatigue method can only improve about 55%. Three methods have obvious improvement effects on stability change of sensors, all of which exceeding 90%, and the vibration aging method can reach more than 95%. By using our equivalent accelerated aging method, the long-term stability of the sensor rated point is better than 0.04% FS, which is obviously better than the original factory aging method. The research results can be used for reference to improve the long-term stability of various silicon-based pressure sensors.

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