Thermodynamic control of MEMS meteorology pressure sensing element in low temperature application down to -45℃

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Abstract: In this paper, we present an alternative method for poor accuracy of piezoresistive meteorology pressure sensing in low temperature environment (down to -45℃) by incorporating external thermodynamic control. In order to use the designed sensor in such a low temperature environment, the MEMS chip itself has to be kept at 50 ℃, which is the most common used highest working temperature in meteorology field. The heat compensation is achieved by a PWM (pulse width modulation) controlled heating resistor based on PID algorithm. The precision of thermal control was obtained at 50 ±0.5 ℃ during the bench test. The simulation results from COMSOL software are consisted with lumped element model analysis. Under the condition of environmental temperature down to -45℃, system achieved a maximum absolute error within ±0.5hPa after pressure calibration.

1. Introduction

Meteorology prediction and analysis are strongly depended on the elements of weather [1]. Among of them pressure is one of the important work. There are some typical pressure sensors such as silicon resonant pressure sensors of GE (General Electric) company and PTB330 of Vaisala Company. They meet the requirements of the meteorological application and have been widely applied in ground stations and sounding instruments. However, they are expensive.

Nowadays, the complex manufacture processes of piezoresistive pressure sensor, like high temperature wafer bonding [2, 3], have been greatly simplified by manufacturers such as STMicroelectronics and Bosch [4, 5]. It makes piezoresistive pressure sensor to be an alternate for meteorology pressure sensing. Usually, piezoresistive pressure sensors exhibited non-linear temperature dependences. Many works have been carried out by variety of groups in recent years to improve the temperature-drift compensation of the sensor such as trimmed parallel resistors and a temperature-dependent series resistor [6] or an additional temperature sensor incorporated into the sensor chip [7]; implemented the digitised curve fitting technique during data disposal [8], analogue or digital signal conditioning circuits used in hardware [9], complicated two-dimensional algorithms [10], ANN (artificial Neural Networks) based CMOS ASIC (Application Specific Integrated Circuit Based on Complementary Metal Oxide Semiconductor Technology) integrated into the sensor [11–14], built-in compensation technique [15]. However, these methods cannot enable the pressure sensor running in a temperature ranged from -40℃ to 50℃. Honeywell Precision Barometer PPT0016AWN2VA-S255 is based on piezoresistive pressure sensor is widely used in meteorology field. But it still expensive. A lot of work need to be done to optimize the accuracy of piezoresistive pressure sensors in temperature down to -40℃. It builds up the cost of pressure sensor.

There is an alternative temperature compensation method which can reduce the cost and is simple as well. By keeping the pressure sensing element in a constant temperature state this method can simplify the temperature compensation of piezoresistive pressure sensors. Drik De Bruyker and Puers [16] had developed an in-chip heating method by sputtering heating resistor in the pressure cavity to keep the sensor at constant temperature. However, the connect wire of heating resistor located between the bonding interface would easily cause the leakage of the vacuum cavity [17, 18]. Nevertheless, it is still not applicable in ambient temperature down to -40℃.

In this paper, we addressed this method through incorporating off-chip heating resistors to dynamically control the temperature of the MEMS pressure chip. The temperature of MEMS chip was maintained in a constant temperature state to allow it to be able to function in a temperature down to -45℃. The following parts of this paper includes: 1) the structure and principle of the sensor; 2) the thermal control and analysis; 3) thermal analysis by lumped element model and COMOSL software; 4) the characteristics of designed sensors.

1. Principle and fabrication
   1. Principle and structure

The principle of thermodynamic control is shown in Fig.1 (a). The temperature of the MEMS chip was measured by microprocessor. Then the measured value was compared with the aimed value (50 ℃). If the temperature of the MEMS chip was higher than the predefined value, the heating resistors will stop heating, vice versa. By PWM controlled heating, the MEMS chip was kept at 50 ℃, which is the most common used highest working temperature in meteorology field. Theoretically the thermal mass is the packaged MEMS chip (dimention:8mm\*8mm\*4mm). In fact, the thermal mass will include the PCB and protecting cap as well. The duty cycle of PWM is automatically calculated by microprocessor with PID algorithm. This constant temperature will not vary with the variation of ambient temperatures. By setting the MEMS chip in a constant temperature state, the sensor is only necessarily to be calibrated under 50 ℃. This method can allow the designed sensor working in temperature down to -45℃.

The sensor structure is shown in Fig. 1 (b-c). The sensor consists of several parts, including a MEMS pressure chip, a metal cap, heating resistors, a platinum resistor and printed circuit board (PCB). The MEMS Chip was mounted on the PCB and protected by a metal cap. The metal cap, which was adhered on the PCB, had a tube which couples the ambient pressure with the MEMS chip. The platinum resistor, which was used to measure the temperature of the MEMS chip, was embedded in the centre of PCB and also connected with the bottom centre of the MEMS chip via silicone grease for better thermal conducting. Heating resistors were mounted on another side of PCB and covered by protect gel. The control PCB, which contains a temperature control circuit and a temperature test circuit, connected underneath the sensing element.



*Fig. 1 Principle of thermodynamic control and structure of whole sensor*

*(a) Principle of thermodynamic control, (b–d) Structure of whole sensor*

* 1. Fabrication and performance of MEMS chip

The MEMS chip was fabricated by bonding a SOI wafer with a pyrex 7740 glass wafer and was further packaged with a plastic socket shown in Fig. 2 (a) and (b). The main fabrication processes are presented as follows. First of all, a golden layer was deposited on the device layer and was patterned to form electronic connections and pads. Then, Deep Ion Reactive Etching (DIRE) was used on the device layer to form strain gauges. Subsequently, DIRE was used to make the cavity on the handle layer of the SOI wafer until the pressure membrane reaches a thickness of 15 µm. After the above step, golden electronic connections and pads were annealed under nitrogen protection. Finally, the patterned silicon wafer and the glass wafer were bonded by anodic bonding with a surrounding pressure of 10-4 Pa.

The latter processes were designed to package the chip. Firstly, the wafer level chip was died to single ones and tested by a probe station. Secondly, the chip was attached with a capsule by silicon glue. Thirdly, the chip and the capsule were placed in a plasma machine to remove impurities. Then, the chip and the capsule were bonded with an ultrasonic bonding machine to connect the chip pad with the capsule pad. Furthermore, the chip and the capsule were aged under temperature of 80 ℃. Finally, the capsule was potted with silicone gel 184.

Typical performances of the MEMS chip without temperature control are shown in Fig. 2(c). The Pressure-Voltage characteristic suggested a precision within 0.15% in square fitting, a sensitivity 6 µV/hPa/V and hysteresis error about 0.7% FSO. The temperature coefficients (TCO) are quantified as about 2718 ppm/℃.



*Fig. 2 Photograph of MEMS chip*

*(a) MEMS chip, (b) Package, (c) Performance of MEMS chip*

1. Thermodynamic Control

The thermodynamic control is realized by microprocessor (C8051F320) and shown in the right of Fig 1. The base of transistor is directly connected with a pin of microprocessor by a base resistor Rb1. The supply Vc is connected to the base of transistor with a resistor Rb2 and connected to the collector of transistor with a resistor Rc. The emitter of transistor is connected with a low resistance resistor which was used as heater. The microprocessor compared the aimed temperature value with the value of Platinum resistor which was used as temperature feedback. Then the PWM module of microprocessor will control the current in transistor. PID algorithm was introduced to change the duty cycle of PWM.

The PID algorithm is crucial in the sensor development. Since the invention of PID control in 1910 and the Ziegler–Nichols’ (Z-N) straightforward tuning methods in 1942 [19], the PID control has been widely used. The equation of the PID algorithm is expressed by [20]

G(s) = Kp + Ki /s + Kd \*s (1)

Where Kp is the proportional gain, Ki is the integral gain, and Kd is the derivative gain. For optimum performance, Kp, Ki and Kd are mutually dependent in tuning. In practice, the equation (1) was rewritten as

Value = Kp \* Error + Ki \*Sumerror + Kd \*Derror (2)

Where, Value is the value used to adjust the output voltage in program, Error is the difference between set value and real value; Sumerror is the sum of the all past errors; Derror is the difference between the current error and the previous error. The parameters (Kp, Ki and Kd) will vary with the structure and the material of the sensor.

1. ****Thermal Analysis****

The main problem of thermal analysis is whether the MEMS Chip works in the aimed constant temperature. It is mainly determined by the power of heater and system thermal structure.

The energy balance equation can be expressed:

 (3)

Where, Pheater is the power of heater, Rst is a generalized thermal impedance of the system to the ambient including conduction, convection and radiation losses, Ts the temperature of the system, Tamb is the ambient temperature, and Csc is the system’s thermal capacitance. In the static state shown as equation (4) the aimed constant temperature of MEMS Chip can be calculated in terms of the equivalent thermal resistance.

 (4)

In the transient state shown in equation (5) the system response time can be obtained from the equivalent thermal capacitance and resistance.

 (5)

* 1. Lumped element model

Thermal domain analysis is similar to the electrical domain. The through variable is the thermal power and the across variable is the heat flow. According to the geometry and material properties, the thermal resistance and capacitance was calculated and shown in table.1.

**Table 1** Material properties, thermal resistance and capacitance in sensor

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Item | Thermal conductivity (k)  (Unit: W/(m·K)) | Specific heat(cp)  (Unit: J/K) | Density (ρ)  (Unit: kg/m3) | Heat transfer coefficient (h)  (Unit: W/(m2•K) | Equivalent thermal resistance (R)  (Rcond=l/(kA)l:length, A:cross section)  (Rconv=1/(hA) A:cross section) | | Equivalent thermal capacitance (C)  (cp\*ρ\*V, where V is volume) |
| protect gel | 0.2 | 1460 | 970 | - | conduction | 50 | 0.141 |
| PCB | 0.3 | 1369 | 1900 | - | 23 | 0.3721 |
| Pt | 35 | 730 | 3965 | - | 6.3 | 3.26e-3 |
| MEMS Chip | 130 | 700 | 2329 | - | 2 | 2.608e-2 |
| Plastic package | 0.2 | 900 | 2700 | - | 1286 | 0.141 |
| Silicone Gel | 0.27 | 1460 | 970 | - | 579.3 | 2.832e-2 |
| Heater | 35 | 730 | 3965 | - | 1 | 2.084e-2 |
| Air Gap | - | 1006.1 | 1.29 | 5 | convection | 222 | 1.56e-4 |

The lumped element model was shown in Fig. 3. In the model, thermal conduction and thermal convection are taken into account. The thermal radiation in room will not occur when the temperature below 1300K [13]. The metal cap was taken as ideal heat sink approaching the ambient temperature. Thus, it was omitted in the lumped element model. A constant current source represents the heater controlled by PID algorithm in MCU. And the ambient temperature is modelled as an extra DC supply. Air convection (air gap in Fig. 3) between the metal cap and MEMS chip is taken into the lumped element model to enhance the accuracy of the model.



*Fig. 3 Lumped element model of thermal system*

First of all, the static performance was studied by running a DC sweep with the power P range from 0 to 0.2 W. The ambient temperature was set to -50 ℃ which exceeded the requirement of application in meteorology. And the constant temperature of chip was set to 50 ℃. It was shown in Fig. 4 that the resulting temperature has a linear response to the heating power. The difference between Theater and Tchip at cursor position Y1 is about 0.9 ℃. When the power is about 0.16 W the chip temperature is about 49.98 ℃. Here the air gap between MEMS chip and Metal cap takes an important role in keeping the chip work at a constant temperature. If it was removed the system will need about 0.25W to keeping the chip temperature. Secondly, the transient performance was conducted. The initial temperature was also set to -50 ℃. The results shown in Fig. 5 suggest that the system will be stable at 49.68 ℃ after running about 1500s. The relative long settling time is led by the large thermal conductivity of Plastic package and Silicone Gel.



*Fig. 4 Multisim DC simulation results of temperature of heater and chip*

*versus power with and without air gap*

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*Fig. 5 Multisim transient simulation results*

* 1. FEM Simulation

The sensor structure is simulated in COMSOL software. The results are shown in Fig. 6. The geometry and material properties used in COMSOL are same with Lumped element model. The ambient temperature was also set to -50 ℃ and the constant temperature of chip was set to 50 ℃.

It was shown in simulation results that the temperature of MEMS chip was about 50 ℃ when the power was 0.16 W. It is nearly equal to the calculation of the lumped element model. If the heating power was changed from 0W to 0.2W at an interval 0.02W, the temperature response can obtain with power variation shown in Fig. 7. The curve is nearly same with that in Fig. 4. But the difference temperature between the heater and the chip was about 9 ℃. The reason is that thermal conduction is more complicated than the assumption in lumped element model. COMSOL software take more thermal conduction factor into calculation processes. But we just think thermal conducts from heater to Pt, PCB and protect gel in the lumped element model. It will not affect the design of the sensor structure.



*Fig. 6 Results of COMSOL simulations*



*Fig. 7 Power–temperature curve of COMSOL simulation*

It is also shown in the thermal distribution of MEMS Chip that the temperature is consistent in the whole membrane. It will not affect the strain detection by the piezoresistor on the membrane. Thus, it is feasible that the MEMS Chip runs at a constant temperature without thermal strain effect.

1. Experiments and Discussion

In order to test the sensor, we developed a sensor system shown in Fig. 8. It includes five parts: a sensor, an outermost shell, a Gas nozzle, a power, and a communication module. The sensor is connected with the test PCB with pins to reduce the thermal conduction. In monitoring of atmosphere pressure, the accuracy of pressure measurement is at least 0.5hPa, which is about 0.05%. Thus, the resolution of the system needs to be less than ±0.1hPa. Provided the pressure sensor’s output in the full scale is 70 mV, we have to use an ADC Converter which can at least detect 7μV. Thus, a 24-bit AD7793 (high resolution ADC Converter), which can sense 0.1 μV, is used to measure the signal of the pressure sensor.



*Fig. 8 Sensor system*

The measurement setup is shown in Fig. 9. In the setup, a barometer (Model 745A made by Paroscientific Inc) was used as the controller which stability is smaller than 0.5 Pa. And Pt 100 was used as the temperature sensor. The fluctuation of temperature in setup is smaller than 0.3 ℃. The output of the sensor was mainly affected by pressure and temperature. Normally, if the temperature is constant, the output is linear to the variation of pressure. If the pressure is constant, the output is nonlinear to the change of temperature. Thus, there are two kinds of calibration methods, which are 1) constant temperature with pressure variation and 2) constant pressure with temperature variation. In our setup, firstly, both approaches need time to become stable. Secondly, temperature of the capsule could change with the variation of pressure. Therefore, it needs more time if the sensor is calibrated under the condition of constant pressure. In the designed sensor, we firstly calibrated and compensated the devices under the temperature which is equal to the set value in a PID algorithm. Then, we tested the designed sensor with the method of constant temperature in response to pressure and temperature variation.

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*Fig. 9 Measurement setup*

* 1. Temperature Control

It is important to acquire the PID parameters accurately to control the temperature in the designed sensor system. The PWM frequency and the heating power are two key factors to obtain PID parameters. The frequency of PWM is controlled by microcontroller C8051F320 (system clock is 12MHz, PWM module is configured as 16 bit mode). It can be modified by changing the PWM clock. It is shown that the temperature of sensor system can be maintained into a constant state when the PWM clock is equal to the system clock of microcontroller C8051F320. Thus the PWM frequency is about 183.1Hz (12MHz divides 65536 equals to 183.1Hz) .

Heating power is another key factor. According to the equation (6) the smaller the resistance of heater the higher the heating power is. However, if the resistance is too small the system will have a big temperature overshoot.

 (6)

In the designed sensor system the maximum heating power should be able to heat the system from -50℃ to 50℃.The experiments were carried out by gradually reducing the resistance of heater with the supply 5V. It is shown that the heating power can satisfied the requirement of sensor system when the heating resistor is 5Ω.

Now the PID parameters can be disposed. Usually, the most common used highest working temperature is 50℃ in meteorology field. Therefore, we set the aimed temperature to 50℃ to PID algorithm. Then, the parameters of Ki and Kd in PID algorithm was set to zero. We gradually adjusted the value of Kp in the PID algorithm until the temperature of the sensor is close to 50℃. Subsequently, we gradually increased the Ki to diminish the control error between the sensor temperature and the controlling temperature. Finally, we adjusted the Kd until the sensor temperature was stable. After these experiments, the parameters in PID algorithm were obtained (Kp =18, Ki=0.15 and Kd =100). For the purpose of thoroughly checking temperature control, the experiments were carried out under ambient temperature ranged from -50℃ to 45℃ with a constant pressure of 1000 hPa. The temperature control results are shown in Fig. 10. It is suggested that the designed sensor can reach temperature stable state with a precision ±0.5 ℃. The higher the ambient temperature the faster the sensor will be settling. When the ambient temperature is -50 ℃ the sensor system reached the stable state after about 1400s. It is nearly in conformity to the analysis in lumped element model. Once the sensor system is stable, it will not delay with the change of the ambient temperature. The temperature control will automatically keep the chip into the predefined temperature.



*Fig. 10 Temperature control results*

So far, the performances of heating part have been illustrated under different ambient temperature with one set of PID parameters. It is sure that the long settling time can be reduced by increasing the heating power and the frequency of the PWM and changing the PID parameters when the ambient temperature is low. However, the ambient temperature seldom severely changed. The system will soon enter another stable state when the ambient temperature changed when the sensor system has already been in a stable state. Thus, the heating part can be used at this moment. In future, it can be further optimized by changing the microcontroller to advanced one and increasing the heating power and the frequency of the PWM.

* 1. Performance of sensor

We compensated sensors by the method developed in this paper in an ambient temperature ranged from -45℃ to 45℃ at an interval of 30℃ shown in Fig. 11 (a). It is suggested that the developed sensor can properly work. The error curve is shown in Fig. 11 (b). It is suggested that the designed sensor has a maximum absolute error within ±0.5hPa.

The power consumption of the heating part in the sensor system was evaluated. The characteristics between current of system and ambient temperature were shown in Fig. 12. It is shown that the minimal current (Imin) was 127 mA when the ambient temperature is 50 ℃ and the maximal current (Imax) was 220mA when the ambient temperature is -50 ℃. The heaters nearly don’t work when the ambient temperature is over 50 ℃. Thus, the current of sensor system besides the heating part (Iother) can be taken as 127mA supposing the power consumption besides the heating part does not change with the ambient temperature variation.



*Fig. 11 Sensor's behaviour under different temperatures*

*(a) Measurement value, (b) Error*



*Fig. 12 Current of sensor system versus ambient temperature*

*characteristic test results*

Hence, the maximal current of the heating part (Iheater) can be deduced by equation (7).

 (7)

The input power of heating part comes from DC-DC power convertor TPS62173 which input voltage is 12V and output voltage is 5V. Thus the input power Pin of DC-DC power convertor can be obtained by (8).

 (8)

Given the conversion efficiency of DC-DC power convertor is 100% the output current IDCout of DC-DC power convertor can be obtained by (9).

 (9)

The resistance of heater in sensor system is 5Ω. Thus the heating power Pheater of sensor system can be calculated by (10).

 (10)

In fact, the DC-DC power convertor will use power as well. Given the conversion efficiency is 75% the heating power will be 0.18W. This value is very close to the simulated result 0.16W. The different may be caused by the parameters of silicone gel used in MEMS chip packaging because its parameters varied with the mass ratio of A and B component.

At the whole sensor system point of view, the maximal power consumption is about 2.64W. Although the power consumption of the whole sensor system is high for meteorology monitoring it will not pose an objection in application because where sufficient power is available. From the PCB point of view, we can optimize the power consumption the sensor system as well.

1. Conclusion

An alternative temperature compensation method, which can reduce the cost and is simple, is presented in this paper. By keeping the pressure sensing element in a constant temperature state this method simplifies the temperature compensation of piezoresistive pressure sensors. It is realized by incorporating heating resistors with the MEMS chip. The heat compensation is achieved by a PWM (pulse width modulation) controlled heating resistor based on PID algorithm. The feasibility of the designed sensor is thoroughly studied by lumped element model and finite element analysis. The simulation results from COMSOL software are consisted with lumped element model analysis. Under the condition of environmental temperature down to -45℃, system achieved a maximum absolute error within ±0.5hPa after pressure calibration. It is suggested that although the system power consumption is a little bit high, the thermodynamic control method is still an alternative way to make MEMS meteorology pressure sensing element to function in low temperature application down to -45℃. In future, the power consumption can be further optimized by changing the microcontroller to advanced one and increasing the heating power and the frequency of the PWM. It can also be optimize by reducing the power consumption by reducing the power management part which consume the most part of power.

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