Integrated Pressure Sensor with Digital Output

Shaobin Zhan, Qijun Wang
Shenzhen Institute of Information Technology, Shenzhen 518172, Guangdong, China

Tie Kang
China Telecom Anhui branch, Hefei, 230031, Anhui, China

Abstract
With the development of the technology, the pressure sensor shows the tendency towards the miniaturization, intelligence and systematization, and the digital pressure sensor is coincided with this trend. An integrated MEMS pressure sensor is designed based on the piezoresistive pressure sensor and the ZMDI sensor signal conditioner (SSC), which has the digital output and the temperature drift, the zero-drift can be calibrated as well. The characteristics of the piezoresistive pressure sensor and the conditioner ZSSC3036 have been introduced, the performance of the designed integrated pressure sensor system has been given with the measurement result. The error is less than 0.55% with the pressure between 100hPa and 1000hPa and less than 0.1% with the pressure between 5hPa and 100hPa at the room temperature.

Key words: Pressure Sensor, Sensor Signal Conditioner, Digital Output

1. INTRODUCTION
Accurate information about the pressure is one of the great important parameters in the life and research area, such as military, aerospace, agriculture, transportation and so on. With the development of the technology of MEMS (Barlian, 2009; Hao, 2014), various kinds of MEMS pressure sensor come into world. Compared with the traditional pressure sensor, the pressure sensor with MEMS technology has the superiority like: small volume, low power consumption, good reliability and ease of integration (Fraga, 2012; Suja, 2013). Several types of MEMS sensors have been studied to detect pressure, for instance, piezoresistive, capacitive, resonant and fiber optic, on which piezoresistive pressure sensors are one of the most widely studied devices for different types of applications such as biomedical, automotive and aerospace. Obviously, a conclusion can be made that MEMS is the future.

However, most of the digital sensor in domestic use discrete device to develop the processing circuit. It is easily to be constructed, but the volume is large and integration level is low. The last four decades had witnessed progress made towards combining integrated circuits (IC) with microelectronicmechanical systems (MEMS). In early 1960, first MEMS based piezoresistive pressure sensors were developed. But first integration of MEMS device with IC was reported in 1990’s. MEMS technology includes fabrication of large structures by surface micromachining, bulk micromachining and LIGA (Lithographie Galvanoformung Abformung). Nowadays the silicon piezoresistive pressure sensor is considered a mature technology in the industry.Hence, single integrate or multi-integrate MEMS devices with IC has becoming a major challenge. The mature products are mostly all from abroad including Freesacle, Bosch, EMAS and so on.

In this paper, an integrated digital MEMS pressure sensor was designed based on the ZMDI sensor signal conditioner (SSC) and the piezoresistive pressure sensor (Wang, 2011). A joint debugging was carried out between the sensor and the sensor signal conditioner. The analog output of the MEMS sensor could be converted to digital signal through amplification, bias and analog-to-digital conversion. After that, the digital signal was calibrated by DSP. At last, this calibrated data could be exported through the communication interface.

2. SYSTEM ARCHITECTURE
The system mainly consists of two parts: 1) MEMS pressure sensor 2) dedicated processor chip, Figure 1 shows the schematic diagram of the system. The MEMS pressure sensor is developed by our own group which has the following features: wide range, good repeatability, low hysteresis, high sensitivity and so on. While the processor chip is ZMDI S16-bit sensor signal conditioner (SSC), which integrated a 18-bit calibration math DSP to running a correction algorithm to accomplish the compensation of sensor offset, sensitivity, temperature drift, and non-linearity. Calibration coefficients are stored in a highly reliable, non-volatile, multiple programmable memory (MTP). The serial interface of ZSSC3036 and control software provided by ZMDI can simplify the programming.
3. SENSOR CHIP

Since the successful development in the late 1950s, piezoresistive pressure sensor is the most mature MEMS sensor. Because of the significant piezoresistive characteristic and mature manufacturing technology, the doped silicon crystal is used in the MEMS pressure sensor. Figure 2 shows the SEM picture of the structure of the sensor used in the design. A silicon film is formed by means of silicon process technology on the sensor and four resistors to form a Wheatstone bridge are made by diffusion technique on the edge of the film, because on the edge the largest resistance variation can be got under the pressure.

In order to measure the change of the resistors conveniently, Wheatstone bridge is used, which connects four resistors into a closed loop. The junction of R1 and R2 is linked to the VCC and the junction of R3 and R4 is linked to GND. While the other two junctions are linked to signal. Figure 3 shows the schematic of the Wheatstone bridge, R1 and R4 are variable resistor fabricated in the membrane, the resistance of which can be changed with the pressure. R2 and R3 are fixed resistor, the resistance of which are constant. The value of R1, R2, R3 and R4 are equal in vacuum because the film does not change.

If the power is VDD, the output signal is:

$$V_{out} = V_{DD} \left( \frac{R_1}{R_2 + R_4} - \frac{R_3}{R_1 + R_3} \right)$$  \hspace{1cm} (1)

If R1=R4=R+ΔR, R2=R3=R, then

$$V_{out} = V_{DD} \left( \frac{\Delta R}{2R + \Delta R} \right)$$  \hspace{1cm} (2)

Because $\Delta R$ is much smaller than R, the denominator can be used as constant, then the output is proportional to $\Delta R$ approximately.
4. PROCESSOR CHIP

4.1. ZSSC3036

The ZSSC3036 is a sensor signal conditioner (SSC) integrated circuit with high accuracy amplification and analog-to-digital conversion of a differential input signal. Designed for high-resolution altimeter module applications, the ZSSC3036 can perform offset, span, and 1st and 2nd order temperature compensation of the measured signal. Developed for correction of resistive bridge sensors, it can also provide a corrected temperature output measured with an internal sensor.

The measured and corrected bridge values are provided at the digital output pins, which can be configured as I2C or SPI. Digital compensation of signal offset, sensitivity, temperature, and non-linearity is accomplished via an 18-bit internal digital signal processor (DSP). Programming the ZSSC3036 is simple via the serial interface. The IC-internal charge pump provides the MTP programming voltage. The ZSSC3036 provides accelerated signal processing in order to support high-speed control, safety, and real-time sensing applications.

Features:
(1) Flexible, programmable analog front-end design; up to 16-bit scalable, charge-balancing two segment ADC
(2) Fully programmable gain amplifier accepting sensors from 14 to 72 (linear factor)
(3) Digital compensation of individual sensor offset; 1st and 2nd order digital compensation of sensor gain as well as of 1st and 2nd order temperature gain and offset drift
(4) 16-bit conditioned sensor signal measurement rate at more than 200s-1
(5) Typical sensor elements can achieve accuracy of less than ±0.10% FSO** @ -40 to 110°C

4.2. ZSSC3036 Block Diagram

Figure 4 shows ZSSC3036 functional block diagram. The ZSSC3036 supports two operational modes: Normal Mode and Command Mode. Normal Mode is the standard operating mode. The sensor bridge supply VDDB and the power supply for analog circuitry are provided by a voltage regulator, which is optimized for power supply disturbance rejection (PSRR). The state machine controls the analog circuitry to perform the three measurement types: bridge, temperature, and offset measurement.

4.3 Analog Front End

The amplifier has a differential architecture and consists of two stages. The amplification of each stage and the sensor bridge gain polarity are programmable via settings in the Measurement Configuration Register. Changing the gain polarity is achieved by inverting the chopper clock.

The analog-to-digital converter (ADC) is used to convert the amplifier signal. To allow optimizing the trade-off between conversion time and resolution, the conversion is split into a MSB coarse conversion and an LSB fine conversion. The final ADC resolution is determined by MSB + LSB. The conversion time is proportional to 2MSB + 2LSB. During the MSB coarse conversion, the ADC input signal is sampled and integrated 2MSB times, resulting in inherit low-pass behavior and noise suppression. The longer the MSB coarse conversion is, the better the noise suppression is. Useful MSB/LSB setups are with LSB = 0 or MSB + LSB ≤ 16. Resolutions beyond 16-bit mainly digitize the collected front-end noise and typically do not improve the system performance.

The ADC offset is programmable in 8 steps so that the ADC input voltage range can be adapted to the voltage range at the input pins INP and INN.

The ZSSC3036’s memory is designed with an OTP (one-time programmable) structure. The memory is organized in 4 one-time programmable pages. When data in the currently valid memory page needs to be
updated, normally a new page must be selected by increasing the page counter. The user has access to a 24 x 16 bit storage area while dedicated calibration values are stored in an area not accessible to the user. There is no over-write or erase function for the MTP memory. Figure 5 shows the memory program operation.

![Figure 5. Memory Program Operation]

5. CALIBRATION AND ANALYSIS

5.1 Parameter Choice

1) Firstly, two parameters are got:
   a. Minimum differential output voltage: \( V_{\text{min}} \)
   b. Maximum differential output voltage: \( V_{\text{max}} \)

2) If the absolute value of \( V_{\text{max}} \) is bigger than the absolute value of \( V_{\text{min}} \), then the gain polarity is positive. If this is not the case, the gain polarity should be reversed.

3) Based on the two parameters, a ratio is got:

\[
Gain_{\text{opt}} = \frac{V_{\text{min}}}{(V_{\text{max}} - V_{\text{min}})}
\](3)

Then A2D_Offset is set to be the nearest value of the integer multiples of 1/16.4) a. if Ratio_Offset-A2D_Offset \( \leq 0 \), then the theoretical gain should be:

\[
Gain_{\text{opt}} = (1 - A2D_{\text{Offset}}) \times \frac{V_{\text{ref}}}{V_{\text{max}}}
\](4)

b. if Ratio_Offset-A2D_Offset \( > 0 \), then the theoretical gain should be:

\[
Gain_{\text{opt}} = \frac{A2D_{\text{Offset}} \times V_{\text{ref}}}{V_{\text{min}}}
\](5)

(Vref is the voltage generated by circuits, the value of which is 1.5V approximately)

5) Finally, choose the closest bridge gain to the \( Gain_{\text{opt}} \) and the bridge gain should be smaller than \( Gain_{\text{opt}} \).

5.2 Testing and calibrating

1) The power and communication mode are chosen by jumpers. Internal power and IIC are selected.
2) Initiating the software, parameters should be set as the values in section 4.1, and then be written to the shadow register.
3) Choosing calibration type, setting relevant temperature and pressure, then starting the measurement. Table 1 shows calibration points and types.
4) 18-bit calibration math DSP run a correction algorithm to get the calibration coefficient.
5) Writing the coefficient and setting to MTP.

<table>
<thead>
<tr>
<th>Table 1. GUI of Calibration Points and Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (%)</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
</tbody>
</table>
The type we choose is 7-points mode, three temperature points and three pressure points are needed. Basing on the seven points, ten coefficients are calculated:
1. Bridge gain (GAIN_B): 53795
2. Bridge offset (OFFSET_B): -15813
3. 1st-order temperature coefficient of the bridge gain (TCG): 1914
4. 1st-order temperature coefficient of the bridge offset (TCO): -6073
5. 2nd-order temperature coefficient of the bridge gain (SOT_TCG): 7020
6. 2nd-order temperature coefficient of the bridge offset (SOT_TCO): 14504
7. 2nd-order term applied to the sensor bridge readout (SOT_B): 282
8. 2nd-order term applied to the temperature reading (SOT_T): -3026
9. Temperature gain (GAIN_T): 101684
10. Temperature offset (OFFSET_T): -12093

Basing on the coefficient above and the formula as follows, real pressure and temperature can be got.

Bridge:

\[
\Delta T = T_{RAW} - T_{SEL} \tag{6}
\]

\[
K_1 = 2^{\Delta T} + \frac{\Delta T}{2^{15}} \times (SOT_{Tcg}^{15} \times \Delta T + T_{cg}) \tag{7}
\]

\[
K_2 = \text{Offset} + BR_{RAW} + \frac{\Delta T}{2^{15}} \times (SOT_{Tco}^{15} \times \Delta T + T_{co}) \tag{8}
\]

\[
Z_{bp} = \frac{\text{Gain} - B}{2^{15}} \times \frac{K_1}{2^{15}} \times K_2 + 2^{15} \tag{9}
\]

\[
B = (Z_{bp} / 2^{15}) \times (SOT_{bridge}^{15} \times Z_{bp} + 2^{15}) \tag{10}
\]

Temperature:

\[
Z_{T} = \frac{\text{Gain} - T}{2^{15}} \times (T_{Raw} - \text{Offset} - T) + 2^{15} \tag{11}
\]

\[
T = (Z_{T} / 2^{15}) \times (SOT_{T} \times Z_{T} + 2^{15}) \tag{12}
\]

Figure 6. The error of the measurement  
Figure 7. The value of the measurement

Figure 6 and Figure 7 were obtained under the temperature of 0°C and 22.5°C. A conclusion can be got that the performance is great. Under the temperature of 0°C, the error is less than 0.8% with the pressure between 100hPa and 1000hPa and less than 0.15% with the pressure between 5hPa and 100hPa. Meanwhile, the error is less than 0.55% with the pressure between 100hPa and 1000hPa and less than 0.1% with the pressure between 5hPa and 100hPa under the temperature of 22.5°C (room temperature). With the condition of 0°C, the error is bigger because the temperature message given by SSC is not accurate enough in this condition.
6. CONCLUSION

In this paper an integrated MEMS pressure sensor has been designed based on the ZMDI sensor signal conditioner and the piezoresistive pressure sensor, which has the digital output and the temperature drift, the zero-drift could be calibrated as well. The error is less than 0.55% with the pressure between 100hPa and 1000hPa and less than 0.1% with the pressure between 5hPa and 100hPa under the temperature of 22.5 °C (room temperature). Meanwhile, the designed digital pressure sensor is of important value in theory and practice.

Acknowledgements

Supported by Training plan of Guangdong Province outstanding young teachers in Higher Education Institutions(Grand No. YQ2013194) and Shenzhen strategic emerging industry development funds(JCYJ2014041810063634).

REFERENCES