Investigation on an Active Thermoelectric Vacuum Sensor with Low Frequency Modulation

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Abstract. In this research, we propose and investigate a thermoelectric-type vacuum sensor with an active heater in the center of sensor under low frequency modulation. Thermal type sensor for vacuum measurement with active-heating is proposed for the suspended thermoelectric element to reach a better performance. Using the TSMC 0.35 μm CMOS-MEMS process, the proposed thermoelectric sensor with active heater is designed and fabricated with central-symmetrical thermocouples positioned. There are 64 pairs of thermocouples placed around the center of membrane and each thermocouple is designed with two kinds of material, n+ Poly and metal. The material of Metal 1 ~ Metal 4 layers is aluminum, and titanium is used as contact layers to connect these metal layers. The total resistance of the structure with four units is measured to be about 14.8 kΩ and the resistance of each unit is about 3.7 kΩ. Four quarters of sensing units of thermopile were connected and the sensing area at the center will give a temperature difference. According to the Seebeck effect, serial connected thermocouples will produce a weak voltage difference between the hot and cold junctions after heat exchange under air convection related to vacuum pressure. The heating of thermopile by active heater is proceeded under different frequencies and the output signal is acquired with a Phase-Lock-Loop (PLL) amplifier. When the periodic heat exchange will take away the heat to cause a temperature drop of sensing area gives a corresponding periodic weak voltage between the cold and hot end of the thermocouples. According to a careful investigation of the PLL measurement with a wide range of 10 m~100 Torr, our proposed sensing scheme based on a thermoelectric type sensor is proved for practical vacuum detection. Most of all it is proved as a new approach to use a commercial thermopile with heater, which is easier to include than a special custom design.

1. Introduction
With the rapid advancement of MEMS process technology, the size of the vacuum gauge has gradually become smaller. From the research literature of the vacuum gauge from 2005 to 2017, it can be found that the development of the vacuum sensor focused on the microelectromechanical processes and CMOS processes. Some papers propose different approaches to improve vacuum response measurement, or to extend the sensing range of the vacuum gauge in a special process. For these researches, the heat sensing for micromachined transducers are popular for applications that are of interest for vacuum sensing because the microelectromechanical industry with outstanding advances in semiconductor process develops rapidly. Application of this new technology for vacuum sensing enables products miniaturized in nanometer, at the same time, improves its performance, as well as reliability and reduces the cost of manufacture [1].

Especially, vacuum sensors intended for measurements of pressures below atmospheric are developed by using well-known and mature CMOS-MEMS devices which explore many important applications [2]. Thermopile-based MEMS vacuum sensors [3] give a new approach with mature integration of MEMS sensors and circuits and bring advantages with wide pressure range. The thermopile devices based on Seebeck effect are also utilized for gas flow sensors, vacuum detectors, thermal converters, etc. Some researches reveal a broad range of commercial applications [4-7].
2. Sensors and sensing scheme

2.1. Design and fabrication of proposed Metal-N-Poly thermoelectric-type sensor.
Using the standard CMOS TSMC 0.35 μm process and CMOS materials the proposed vacuum sensor is fabricated in Fig. 1. A series of post-processes including an isotropic RIE and wet etching processes are proceeded after the CMOS processes to remove the silicon under the sensing structures. Each thermocouple is fabricated with standard CMOS materials of the Metal 4 layers and N-polysilicon which is serial connected to each other. There are 64 pairs of thermocouples around the centre of sensing membrane. To remove the silicon substrate beneath the membrane efficiently, we design the etching windows of slim-long type situated between each two thermocouples which allow the etchant to flow through. The active area of thermopile is around 800x800 μm².

![Figure 1.](image)

Figure 1. (a) Schematic drawing of thermopile structure; microscopic picture of (b) full chip after fabrication and (c) a quarter of the thermopile.

2.2. Proposed sensing scheme for thermoelectric-type sensor.
Installed in a vacuum chamber, the active heater of thermopile sensor is operated under periodic modulation of heating which acts as a heat source for the sensing membrane. Besides of the parameters of operation in our experiment structure, the sensitivity of vacuum sensor also depends on thermal properties including the heat capacity and heat conductance which is governed by the heat equation.

3. Measurement for proposed thermoelectric type sensor
The experimental structure includes a vacuum sensor, an input signal source, a vacuum chamber and a PLL amplifier, which is shown in Fig. 2. The input signal resource for the modulation is heating and cooling, and the vacuum sensor for modulation is vacuum level. After amplification and low-pass filtering, the signal is sent to the PLL amplifier. A time constant is setup at 10 seconds to acquire a stable reading for low frequency measurement.
4. Vacuum measurement and analysis

4.1. Voltage vs. frequency.
To investigate the frequency response, the proposed thermoelectric sensor is operated and sensing under the modulated heating for frequency 1~100 Hz at different vacuum conditions. In order to test thermopile output voltage at different vacuum levels, when heater input voltage at different frequencies from low to high, the voltage from the output of the thermopile will be changed, the data is collected and arranged which is shown in Fig.2. The modulation variable of this experiment is mainly the frequency of the heater input voltage. The experimental input voltage amplitude for heater is fixed at 0.5V, the offset voltage is 0.26V which gives a sinusoidal bias voltage to the heater at different vacuum.

![Graph showing the relationship between voltage and frequency](image)

At the same time, we can see that in the Fig. 3, when the input frequency exceeds 20 Hz, the output voltage begins to drop sharply, and when the frequency exceeds 60 Hz, the output voltages of different vacuum degrees are nearly equal.

![Graph showing the relationship between frequency and thermopile voltage](image)
4.2. Voltage vs. pressure.
Moreover, in order to observe that the vacuum gauge uses different degrees of vacuum at the different frequencies of input voltage for heater, the voltage output of the thermopile changes, Fig. 4 changes the X axis to vacuum and the line segment changes to the input frequency. The modulation variables of this experimental are mainly degrees of vacuum.

![Voltage vs. pressure](image)

**Figure 4.** Thermopile voltage vs. pressure of chamber.

Fig. 4 changes the X-axis from frequency to vacuum. When the X-axis becomes vacuum, we can see the change of the thermopile output voltage under different vacuum degrees. In Fig. 4, it can be observed that when the degree of vacuum is lower than 10 Torr, the line segments of different frequencies can be clearly distinguished, but when the degree of vacuum is higher than 10 Torr, the output voltage at different input frequencies is irregular.

4.3. Voltage at different vacuum intervals.
When the heater input voltage with different frequencies and vacuum degree change experiments are completed, the data can be used to obtain trend line of output signal in the different vacuum intervals when the frequency of heater input voltage from low to high, and calculate the sensitivity of the chip under different vacuum degrees which is shown in Figure 5.

Fig. 5 takes frequency as the X axis, voltage as the Y axis, and vacuum as the fitting line of the vacuum range. In this figure, we can clearly see the voltage trend line graph at various frequencies. It shows the frequency of input voltage for the heater from low to high and the change of the sensitivity curve under different vacuum degrees. Between the different vacuum interval curves, it is found that the best sensitivity curve is obtained when the vacuum is 1 Torr to 10 Torr which is shown in Fig. 5. It means that we can find the best measurement sensitivity from these different vacuum intervals. And when we find the best sensitivity, we can confirm the best working vacuum of this vacuum gauge.
5. Conclusions
In this research work, a thermoelectric-type vacuum sensor with heating modulation is proposed and the frequency response within 1 ~100 Hz is investigated. The periodic heating is proceeded based on the sinusoidal heating and PLL reading of the output signal from the amplified voltage of CMOS-MEMS thermoelectric sensor. The proposed thermopile with active heaters is designed and fabricated with 64 pairs by using the TSMC 0.35 μm CMOS-MEMS process and the post MEMS process. The results of vacuum measurement with a wide range of 10 m~10 Torr shows a good signal and better stability under low frequency modulation. A new sensing scheme based on a thermoelectric type sensor is proved for practical vacuum detection at low frequency modulation of heating and this research work is proved as a new approach to use an active thermopile with heater for vacuum measurement.

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