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A CMOS-compatible temperature sensor based on the gaseous thermal conduction dependent on temperature

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ABSTRACT

There are many different types of temperature sensors, including thermal resistor, thermocouple, thermal diode, etc. All the operational principles of them are based on the fact that some property of the sensor material is temperature-related. Based on the fact that the gaseous thermal conductivity of air is linear to the temperature from 250 K to 500 K, this paper proposes a new type of temperature sensor which employs the gas between the microhotplate and its substrate as the temperature sensing component. The temperature sensor consists of the CMOS-compatible tungsten microhotplate fabricated by surface micromachining technology as the heating component, the gas between the microhotplate and the substrate as the sensory material and the constant current circuit as the bias circuit. The heat of microhotplate can be dissipated by the gaseous thermal conduction which is dependent on the gas temperature. The measurement results show that the sensitivity of the sensor is 1 mV/°C and its linearity is 1.48% from −20 °C to 70 °C. The sensor with the inflatable sealed package with N_2 or inert gas can immerge in the gas or liquid atmosphere to measure the temperature.

1. Introduction

Temperature sensor is widely used in the temperature measurement. The most important temperature sensors are the thermal resistor, thermocouple and thermal diode. Some of the temperature sensors are fabricated by the development of the CMOS-MEMS technology [1–3].

All the operational principles of the temperature sensor are based on the fact that some property of the sensor material is temperature-related. The gaseous thermal conduction is mainly affected by the gas temperature, gas pressure and the type of the gas. For a gas in the constant temperature, the gas pressure can be measured which is the principle of the Pirani vacuum sensor [4,5]. Similarly, when the gas pressure and temperature are constant, the type of the gas can be detected which is used for the gas sensor or gaseous thermal conductivity measurement [6,7]. Also, when the gas type and pressure are constant, the gas temperature can be obtained which is the principle of the temperature sensor presented in this paper.

The temperature sensor consists of the CMOS-compatible tungsten microhotplate fabricated by the surface micromachining technology as the heating component, the gas between the microhotplate and the substrate as the temperature sensory component and the constant current circuit as the bias circuit. The temperature can be correlated with the temperature-related gaseous thermal conduction between the microhotplate and its substrate. The measurement results show that the sensitivity of the sensor is 1 mV/°C and its linearity is 1.48% from −20 °C to 70 °C. Besides that, the sensor also has the response to the gas pressure and the types of the gas. With the inflatable sealed package with N_2 or inert gas, the sensor can immerge in the gas or liquid atmosphere to measure its temperature.

2. The operational principle

Fig. 1 shows the typical structure of microhotplate. The microhotplate is suspended by four beams. The resistor in the microhotplate is used as the heating resistor and the temperature measurement resistor. The heat of microhotplate can be dissipated by the following heat loss mechanisms: solid thermal conduction through the supporting beams (Q_s), gaseous thermal conduction above and below (Q_g), convection through gas (Q_c), and thermal radiation (Q_r). Due to small size and usually low operating temperature of microhotplate, the last two ones can always be neglected [8]. Q_g is dependent on the gas pressure (P), temperature (T) and the gas type. Thus, for a constant gas pressure, the gaseous thermal

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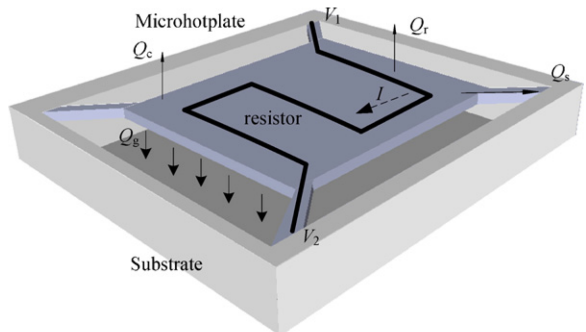

Fig. 1. The structure of the microhotplate.

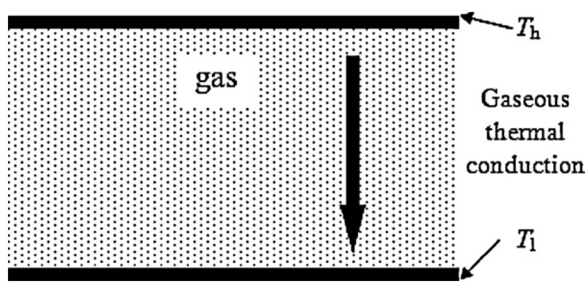

Fig. 2. The gas thermal conduction between the microhotplate and the substrate.

conduction is the function of the temperature of the gas. If a constant current (I) is put through the microhotplate, the electrothermal process can be described by Eq. (1).

$$I^2 \times R_0[1+\alpha(T-T_0)] = Q_g + Q_s \tag{1}$$

where R_0 is the initial value of the heating resistor at T_0 K and α is the temperature coefficient of the heating resistor. The microhotplate can be simplified as a three layers system, seen in Fig. 2. The microhotplate is the layer with the high temperature (T_h) which is induced by the heating current. The substrate is the layer with the low temperature (T_l) and the gas between them acts as the thermal conduction layer.

According to the Fourier's law of heat conduction, Eq. (1) can be rewritten as:

$$I^2 \times R_0[1+\alpha(T_h-T_0)] = k_{gas}(T_{gas})A_g\frac{T_h-T_l}{d} + k_{solid}A_s\frac{T_h-T_l}{L} \tag{2}$$

k_{gas} and k_{solid} are the thermal conductivities for the gas and the solid beams, respectively. A_g and A_s are the area of the thermal conduction for the gas and the beams, respectively. L is the length of the supporting beam and d is the gap between the microhotplate and the substrate. When the temperature increases ΔT, Eq. (2) will become:

$$\begin{aligned} & I^2 \times R_0[1+\alpha(T_h+\Delta T-T_0)] \\ &= k_{gas}(T_{gas}+\Delta T)A_g\frac{(T_h+\Delta T)-(T_l+\Delta T)}{d} \\ &+ k_{solid}A_s\frac{(T_h+\Delta T)-(T_l+\Delta T)}{L} \\ &= k_{gas}(T_{gas}+\Delta T)A_g\frac{T_h-T_l}{d} + k_{solid}A_s\frac{T_h-T_l}{L} \end{aligned} \tag{3}$$

The $V_{out} = V_2 - V_1$ is the output voltage of the sensor which can be calculated as:

$$\begin{aligned} V_{out} &= I \times R_0[1+\alpha(T_h+\Delta T-T_0)] \\ &= \frac{k_{gas}(T_{gas}+\Delta T)A_g(T_h-T_l)/d + k_{solid}A_s(T_h-T_l)/L}{I} \end{aligned} \tag{4}$$

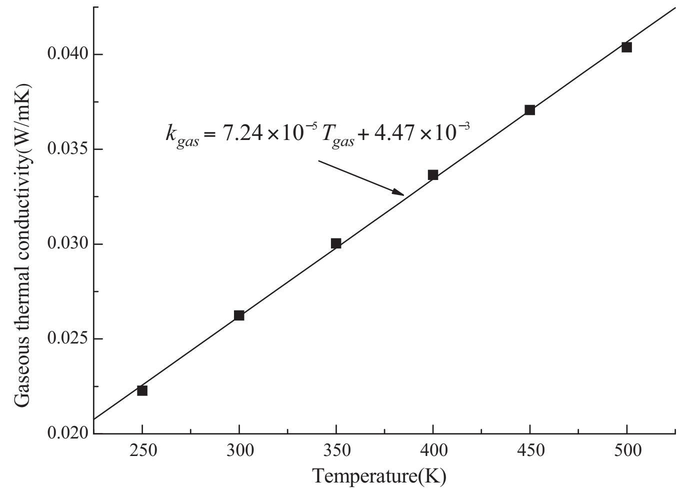

Fig. 3. The air thermal conductivity at atmospheric pressure in different temperatures [9].

k_{gas} is the function of the temperature. From 250 K to 500 K, the thermal conductivity of air is linear to the temperature, seen in Fig. 3. According to Eq. (4), the output voltage is linear to the temperature.

3. Fabrication of the Tungsten microhotplate

Microhotplate is a microheater fabricated by MEMS technology. It is widely used in gas sensor, gas pressure sensor. The major points for microhotplate design are its structure and heating material.

There are two different structures for the microhotplate fabricated by micromachining technology, including bulk-micromachining and surface-micromachining. Bulk-micromachining structure is widely adopted for the gas sensor due to its large area and easy-made. But its disadvantage is its less power efficiency. The gas thermal conductivity sensors described in Refs. [6,7] are fabricated by bulk-micromachining. It is important to consider the sensor power efficiency because a great amount of the heat is transferred by the solid thermal conduction through membrane. In order to optimize the structure, our design is surface-micromachining with four beams connecting to the substrate, which can largely increase the sensor power efficiency.

Also, there are many different heating resistors materials available for microhotplate, such as polysilicon [10], aluminum [11], platinum [12] and tungsten [13]. In this paper, tungsten microhotplate is employed as the heating component due to its high melting point, large temperature coefficient and CMOS-compatible.

Tungsten has been traditionally used as a plug material to form via pathways between various metal layers and the silicon substrate due to its ability to uniformly fill the high-aspect ratio vias when deposited by chemical vapor deposition (CVD) methods. In our design, the tungsten microhotplate is implemented in 0.5 μm CMOS process that features two polysilicon layers (Poly1 and Poly2) and three metal layers (Metal1, Metal2 and Metal3). The metal plug between Metal1 and Metal2 is tungsten, and the one between Metal2 and Metal3 is aluminum due to its larger dimension. All the dielectric layers in the process are adopted as the Phosphosilicate glass (PSG). In the design of the tungsten microhotplate, tungsten is employed as the heater in the form of serpentine resistor instead of via plug. The anchors of the tungsten resistor are connected to Metal2, leaving Metal1 unconnected. A 0.34-μm-thick Poly2 is used as a sacrificial layer below the tungsten microhotplate. The etch windows of the tungsten microhotplate are opened during bonding-pad patterning in a standard CMOS process, as