A thermal micro pressure sensor: its characteristics and application to pressure measurement in a minute package

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A thermal micro pressure sensor suitable for measurement in the range of \(7 \times 10^3\) to \(1 \times 10^5\) Pa was realized by forming a titanium (Ti) thin-film resistor on a floating NSG (non-doped silica glass) membrane, with the sensing area being as small as \(60 \mu \text{m} \times 60 \mu \text{m}\). The sensor performance was raised by increasing the gaseous ratio to the total thermal conduction, compensating the effect of ambient-temperature drift, and utilizing an optimized novel constant-bias Wheatstone bridge circuit. The sensor was successfully applied to monitoring the pressure in a sealed minute metal package with a capacity of about 0.5 ml.

Keywords: micro pressure sensor, thermal conduction, constant-bias circuit, pressure sensing in minute package

1. Introduction

Sensors and actuators in micro sizes, which may have overwhelming advantages in such as functions and cost compared to conventional macro ones, have been taken for granted nowadays due to the remarkable development of micromachining technologies. However, when a device gets down to micro sizes, effects such as friction, sticking and air damping become notable and sometimes may determine the device characteristics. For example, the resonant amplitude and half-value width of a micro oscillator depend strongly on the ambient air pressure due to damping effect, which has been used to detect gas pressure. It is then necessary to package the device under a steady pressure (usually a reduced pressure to obtain satisfactory performance) when the oscillator is used for purposes other than pressure sensing. This directly demands the precise detection of pressure and pressure steadiness in the sealed minute package, which calls for a micro pressure sensor with high resolution and especially, micro sizes.

Various micro sensors have been developed and proposed for pressure detection and may be roughly classified as follows: (i) The aforementioned resonant type \(^1\). One of its shortages is the low sensitivity in pressure regime lower than 1Pa. (ii) The ionization gauge \(^2\). It is expected to be suitable for ultrahigh vacuum measurement. However, since electrons emitted from a cathode must be sufficiently accelerated to collide with and ionize gas molecules, a high voltage circuit and a relatively large device size are always necessary. (iii) The mechanical type. A thin diaphragm is usually used and its deformation caused by pressure difference between the target and the standard pressures is detected by measuring the corresponding change in such as electrostatic capacity \(^3\), piezoelectric resistance \(^4\) or optical quantities \(^5\). The fatal disadvantage of this kind of sensors is the necessity of a vacuum room to supply the pressure standard, whose reliability is also to be evaluated. (iv) The thermal type (the Pirani type) \(^6,7\). The principle is simple: when gas molecules collide with the heated sensing part, heat is taken away in a quantity depending on the molecule numbers, and therefore the gas pressure. Compared to other pressure sensors, the thermal type is superior in possibilities of small size, easy-to-fabricate simple structure and above all, high resolution and wide range. In this work, the thermal sensor is showed a good candidate for high-resolution pressure measurement in a minute package.

2. Sensor Fabrication

The sensor was fabricated by micromachining techniques. A photograph of the sensing part is illustrated in Fig. 1. A schematic of the sensor is illustrated in Figs. 2 a (top view) and b (cross-sectional view). The element is composed of a titanium (Ti) thin-film (80nm thick) resistor \(R_s\) patterned into a square-wave structure and sandwiched by two NSG (non-doped silica glass) thin films (350nm thick each). In order to realize good thermal insulation of solid conduction, the sensing part is cut away from the substrate by a conventional silicon (Si) anisotropic etching method \(^8\), leaving only four narrow beams to support the 60\(\mu\text{m}\times 60\mu\text{m}\) floating membrane. The NSG
membrane not only supports the Ti resistor but also protects it from oxidation. The solid thermal conduction, with the beams as its only paths, is extremely reduced by the low thermal conductivity of NSG and the thin beam design: 0.78 μm thick, 65 μm long and as narrow as 4 μm. A reference resistor \( R_e \), also made from Ti, is simultaneously formed directly on the Si substrate (without thermal insulation) to reduce the ambient temperature \( T_a \) dependence of the sensor characteristics.

3. Sensor Characteristics

3.1 Thermal Conduction

The heated sensor loses heat \( Q_T \) by radiation \( (Q_r) \), solid conduction through the beams to the substrate \( (Q_s) \), and gaseous conduction to both the backside substrate and the forward ambient \( (Q_g) \), which can be simply expressed by Eqs. 1-4:

\[
\begin{align*}
Q_T & = Q_r + Q_s + Q_g \\
Q_r & = \sigma \varepsilon (T_e^4 - T_a^4) A_s \\
Q_s & = K A_s (T_e - T_a) / L \\
Q_g & = \alpha \Delta (273/T_e)^{1/2} (T_e - T_a) A_s P
\end{align*}
\]

where \( \sigma \) is the Stefan-Boltzmann radiation constant, \( \varepsilon \) and \( K \) are the thermal emissivity and thermal conductivity of NSG, \( \alpha \) and \( A \) are the accommodation coefficient and free molecule thermal conductivity of the ambient gas, respectively; \( A_s \) is the total surface area of the membrane, \( A_s \) is the total cross sectional area of the beams by which they are connected to the substrate, while \( L \) is the length of a single beam; \( T_e \) is the ambient temperature, \( T_i \) is the sensor temperature and \( P \) is the ambient gas pressure. For simplicity, only an expression in the free molecular flow regime of \( Q_g \) is showed in Eq. 4.

![Fig. 1. Top-view photograph of the sensing element of a thermal micro pressure sensor fabricated by micromachining techniques.](image)

![Fig. 2. Schematic of the thermal sensor: a) top view, and b) cross-sectional view.](image)

![Fig. 3. Calculated heat losses as a function of ambient gas pressure.](image)

The heat losses \( Q_T, Q_r, Q_s, \) and \( Q_g \) are calculated by using Eqs. 1-4 and plotted against \( P \) in Fig. 3, where the experimental material and device parameters are adopted while the temperatures are assumed as \( T_e = 300K, T_i = 350K \). As obviously observed in Fig. 3, only \( Q_g \) is gas pressure dependent and a \( Q_g \)-based sensor characteristic becomes saturate as \( P < 1Pa \) since \( Q_g \) decreases linearly with \( P \) and occupies a very small ratio.
in \( Q_T \) in the low pressure regime. This implies two ways to expand the sensing range and to elevate the resolution. One way is to extend the molecular flow regime[7] and to increase the \( Q_T/Q_1 \) ratio, which may be realized by proper device structure design basing on the thermal conduction mechanism, but meanwhile, with the experimental permission. Another way is to extract \( Q_S \) from \( Q_T \), which requires tricks of electronic circuitry and signal analysis.

3.2 \( T_s \)-Dependence of Sensor Characteristics

Like other types, the thermal pressure sensor is ambient-temperature \( (T_s) \) dependent. This effect was studied by using a simple Wheatstone bridge circuit with the sensor \( R_s \) as one leg of the bridge (inserts of Figs. 4 and 5). In Fig. 4, when a voltage \( V_o \) is applied, \( R_o \) and \( R_s \) keep constant, while \( R_s \) is heated to temperature \( T_s \) and

\[
R_s = R_{o0} \left[ 1 + C_T \left( T_s - T_{o0} \right) \right],
\]

where \( C_T \) is the temperature coefficient of resistance (of \( T_{o0} \) here) and \( R_{o0} = R_s \left( T_{o0} = T_s \right) \). The circuit operates to keep \( V_{o0} = V_{o1} \) namely, \( R_o = R_{o0} = \) constant. In such a circuit, \( V_s \) is a \( Q_T \)-based quantity. Since \( R_{o0} \) is chosen in such a way that \( R_{o0} = 1.15 \sim 1.36R_{o0} \) at 30°C (it is the same with \( R_s \)), and \( C_T \) is measured to be \( C_T = 0.3 \text{K}^{-1} \), the sensor temperature \( T_s \) is 50~120°C above the ambient temperature \( T_s \) in thermal equilibrium state.

As showed in Fig. 4, a \( T_s \) variation \( (\Delta T_s) \) leads to a \( V_o \)-\( P \) curve shift in proportion to \( -\Delta T_s \), which directly limits the sensing range and resolution. \( R_{o0} \) is then replaced by \( R_s \) (insert of Fig. 5), which has the same \( T_{o0} \) with \( R_s \). In this case, since \( R_s \) is directly located on the Si substrate, a good thermal conductor, its temperature is kept at \( T_s \) even when an electric current flows through it. In thermal equilibrium state, \( R_s = R_s \) is a quantity depending on \( T_s \). As showed in Fig. 5, the sensor characteristic drift is greatly reduced by the compensation effect of \( R_s \). These results are found in good agreement with theoretical calculations.

3.3 Constant-Bias Circuit

According to the theoretical and experimental results showed in Figs. 3-5, it is obvious that a \( Q_T \)-based sensor characteristic has a limited range and a vanishing resolution as \( P < 1 \text{Pa} \). Since \( Q_T \) and \( Q_s \) are independent of pressure and lead to the characteristic saturation in low pressure regime, while \( Q_s \) is the directly measurable quantity, subtracting a constant close to \( Q_T + Q_s \) from \( Q_s \) will help extract information on \( Q_s \). For this purpose, a constant-bias Wheatstone bridge circuit, illustrated in Fig. 6, is employed.

![Fig. 6. Constant-bias Wheatstone bridge circuit for high resolution and wide range pressure detection.](image)
In the circuit, a constant bias \( V_b \) is applied to the bridge in order to realize the subtraction, and the bridge balance \( (V_b=V_1) \) is eventually maintained by a control unit that supplies \( R_s \) a current \( I_s \). \( I_s \) varies corresponding to the gas pressure and is amplified by \( R_L \) and detected as the output voltage \( V_{out} \). In Fig. 6,

\[
V_{out} = R_L I_x
\]

(6)
The current flowing through \( R_s \) is

\[
I_s = I_1 + I_x
\]

(7)
The current flowing through \( R_1 \) is

\[
I_1 = \frac{V_b - V_x}{R_1}
\]

(8)

When the bridge is balanced,

\[
I_s R_s = V_1 = V_x = \beta V_b
\]

(9)

where

\[
\beta = \frac{R_1}{R_2 + R_1}
\]

According to Eqs. 7-9, \( I_s \) can be expressed as

\[
I_s = \frac{V_b}{R_1} - \frac{V_x}{R_1} \frac{V_b - V_x}{R_1}
\]

(10)

While, the power supplied to \( R_s \) by the control unit that balances the bridge is

\[
P_s = \frac{V_s^2}{R_s}
\]

(11)

Here, we define a quantity \( S_r \) as

\[
S_r = \frac{R_r - R_{ma}}{R_{ma}} \frac{1}{P_s}
\]

(12)

As understood from the equation, \( S_r \) is the resistance variation ratio per unit input power, an intrinsic quantity for a given sensor at a fixed ambient temperature. \( S_r \) is named as the power sensitivity of resistance and can be found by simple measurement. By using Eqs. 9, 11 and 12, an expression for \( R_r \) can be obtained:

\[
R_r = \frac{R_{ma}}{2} \left[ 1 + \sqrt{1 + \frac{4S_r V_b^2}{R_s \beta^2}} \right]
\]

(13)

By substituting \( V_s \) and \( R_r \) in Eq. 10 by those given in equations 9 and 13, respectively, \( I_r \) eventually, \( V_{out} \) can be found as

\[
V_{out} = R_L I_x = R_L \frac{I_s}{R_1} \left[ \beta \left( \frac{2R_1 / R_{ma}}{1 + \sqrt{1 + \frac{4S_r V_b^2}{R_s \beta^2}}} + 1 \right) ^{-1} \right] V_b
\]

(14)

A \( S_r-P \) curve measured at 30°C is showed in Fig. 7. The curve indicates that the power sensitivity of resistance is high in the pressure range of 1 Pa < \( P \) < 10^4 Pa, but poor in the two extremes.

The bias voltage \( V_b \) dependence of the output signal \( V_{out} \) is then calculated by using Eq. 14 and the measured \( S_r \) showed in Fig. 7. The result is depicted in Fig. 8. In the calculations, parameters are specified by the same values used in the experiments, as:

\[
R_1 = R_2 = R_{ma} = 10 \, k\Omega
\]

\[
R_s = 7.21 \, k\Omega, \text{ at } 30^\circ C
\]

\[
R_{ma} = 5.29 \, k\Omega, \text{ at } 30^\circ C
\]

![Fig. 7. Measured power sensitivity of resistance versus pressure, of a thermal micro pressure sensor.](image)

![Fig. 8. Calculated and measured sensor characteristics by using the constant-bias circuit showed in Fig. 6. That measured by a simple bridge circuit (insert of Fig. 5) is also displayed for comparison.](image)
It is found from Fig. 8 that the sensor characteristic depends on \( V_n \) strongly, with a value of \( V_n = 2.20 \text{V} \) being the best for the wide range and high resolution purpose in this case. The theoretical prediction is straightforwardly verified by experimental results shown in the figure by black markers. The good agreement between theory and experiment clearly indicates that the optimum \( V_n \) value can be derived from Eq. 14. In fact, all circuit parameters can be optimized in the same way.

For comparison, a \( V_c-P \) curve obtained by the simple Wheatstone bridge circuit (insert of Fig. 5) is also plotted in the figure. Obviously, the sensor characteristic is greatly improved by extracting information on \( Q_n \) with the help of the optimized constant-bias circuit.

4. Pressure Sensing in a Minute Package

The micro sensor and the optimized constant-bias circuit are then applied to the pressure measurement in a minute package. First, the sensor was fixed to a metal base (TO-8) by low-melting-point solder and was bonded to the feedthrough pins by aluminum thin wires. The sensor was then calibrated at 30°C in a vacuum chamber filled with \( \text{N}_2 \) gas. The chamber pressure was read by a MKS digital convection enhanced Pirani gauge (Series 947) in the range of 10Pa < \( P < 10^5 \text{Pa} \), and by an ANELVA digital wide range ionization vacuum sensor (M-430HG-J) in the range of \( P < 10^5 \text{Pa} \). The output signal \( V_{\text{out}} \) was read by a HP 3456A digital voltmeter. Subsequently, the sensor-mounted TO-8 base was sealed with a steel cap by projection welding method, under a reduced pressure. Figures 9 a and b are respectively a photograph of the sealed package and a schematic of its cross section. The capacity of the package is as small as about 0.5ml. Finally, the package was kept in a thermostat at 30°C and the interior pressure \( P_{\text{id}} \) was detected by reading \( V_{\text{out}} \). The obtained time dependence of \( P_{\text{id}} \) is given in Fig. 10.

For the package showed in Fig. 10, \( P_{\text{id}} \) increases dramatically from 160Pa to 290Pa in the first 50 hr after sealing, and then gradually tends to increase at a constant rate of \(-0.04\text{Pa/hr}\). The initial rapid increase of \( P_{\text{id}} \) may be due to the degassing of the package inner walls, the sensor and the solder, and will be reduced by baking the package set in vacuum at above 100°C before welding. The later linear increase of \( P_{\text{id}} \) with time suggests a sealing leakage.

![Fig. 9. A sealed minute package: a) photograph, b) schematic of the package cross section.](image)

![Fig. 10. Pressure in a sealed minute package detected by the thermal micro pressure sensor.](image)

By two methods, the sensor characteristics were proved almost unchanged by sealing and preserving in the sealed package for a long period of time: One method is monitoring the values of \( C_T, R_n \) and \( R_s \) at 30°C. The other method is to open the package gently and recalibrate the sensor.

5. Discussion and Conclusion

The sensing extremes of thermal micro pressure sensors have been well explored \((6, 7)\). In Ref. 6, by stabilizing the substrate temperature to an accuracy of ±0.001°C and by employing a well-developed circuit, the computer-assisted system is capable of measuring a
pressure as low as $10^{-3}$Pa. On the other hand, by creating a heat sink as close as a few μm to the heated sensing part, the molecular flow regime is extended and the sensible upper extreme is extended up to $10^6$Pa (2). These results present the great potentials of thermal pressure sensors. However, a low cost, easy-to-create simple system is often desirable in practice.

In this work, by using a simple micro sensing element and a novel circuit designed according to the thermal conduction principles, satisfactory sensor performance was obtained in spite of the system simplicity. Such a sensor is showed practically useful for pressure detection in a minute package.

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References


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