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Proposal of a new structural thermal vacuum sensor with diode-thermistors combined with a micro-air-bridge heater

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Abstract

New structural Pirani gauge-type thermal vacuum sensor with a microheater and two pn junction diodes, Th-A and Th-B, as a high-sensitive temperature sensor working like a thermistor formed on a micro-air-bridge (MAB) is proposed. The MAB is separated into two regions of A and B. The Th-A and the Th-B can measure temperatures of the region A and the region B connected to the region A with thermal resistance, respectively. The microheater is formed in the region A and can maintain its temperature by feedback control. The diode-thermistor, Th-C, formed on the SOI substrate is provided to measure the ambient temperature T_c. Principle of this Pirani gauge-type thermal vacuum sensor is based on the measurement of the pressure-dependent thermal conductivity of gaseous media due to the heat exchange between the heated MAB (suspended film) and surrounding gas in vacuum. This has more than two orders of magnitude measurable pressure range (2×10^{-3}–1×10^{5} Pa) compared with traditional Pirani vacuum sensor, and has very fast response and low power consumption.

Keywords: Thermal sensor; Vacuum sensor; Temperature sensor; Microheater; SOI; Pn junction

1. Introduction

Principle of the thermal vacuum sensor, such as Pirani vacuum sensor, is based on the dependence of the thermal conductivity and convection of the ambient gas on the pressure in vacuum, namely based on measuring the heat loss of the hot object. The conventional Pirani gauge is for vacuum measurement ranging from 10^{-1} to 10^{4} Pa.

The author, Kimura, has first proposed a micro-air-bridge (MAB) heater fabricated by using silicon planar and micromachining technologies, and suggested that this MAB heater with a temperature sensor will be widely used as a flow sensor, the thermal vacuum sensor, etc. to improve their sensitivities and responses due to a floating thin film [1].

The Pirani vacuum sensor basically consists of a hot wire inside a cylindrical tube acting as a heat sink as shown in Fig. 1. The thermal conductivity λ of the surrounding gas is given as follows:

$$\lambda = \frac{\bar{c}}{2}\frac{C_v}{RT}\,lp\frac{d}{d+2l\left(\frac{2}{\alpha_E}-1\right)}, \tag{1}$$

where $\bar{c}$ is the average molecular velocity, C_v the specific heat at constant volume, R the universal gas constant, T the gas temperature, α_E the energy-accommodation probability ($\alpha_E = 0.77$ for nitrogen on Pt surface), l the mean free path of the gas molecule, p the pressure, and d the distance between heated wire and heat sink [2].

In the high vacuum pressure range ($l \ll d$) the thermal conductivity λ does not change with pressure p, since pressure dependence of l cancels with p from Eq. (1). In the medium pressure range ($l > d$) that the mean free path l of the gas molecule is limited by the distance d, the thermal conductivity λ is proportional to p. In the very low pressure (high vacuum) range, the heat transfer to the gas from the hot wire will approach zero since the number of gas molecules becomes very small and most heat loss is limited by that through supporting beam. So the lower pressure

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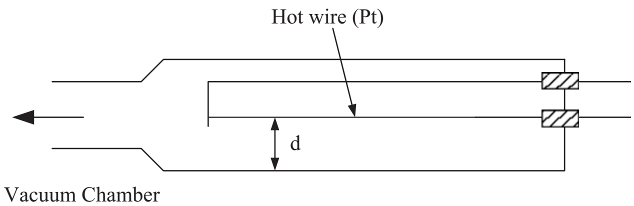

Fig. 1. Structure of the Pirani vacuum sensor.

limit exists. Therefore, there is an operable vacuum range in the thermal vacuum sensor between these two pressure-independent ranges (higher and lower pressure ranges). The measurable range of the vacuum sensor shifts to lower pressure with increasing the distance d.

Since Pirani first reported on the pressure measurement using the thin wire in vacuum based on the measurement of the thermal conductivity of the gas in 1906 [3], many efforts on improvements of sensitivity and measurable pressure range of the Pirani vacuum sensor had been reported, including recent improved thermal vacuum sensors by means of micromachining technologies [4–13].

Herwaarden et al. have first demonstrated the sensitivity of the Pirani gauge by the use of the hot floating membrane (MAB) and thermopile as a temperature sensor instead of the hot wire of Pirani gauge [9].

Berlicki et al. have analyzed the ambient temperature influence on the performance of thin-film sensor, fabricated in a thin-film process and have improved the sensitivity of the thin film vacuum sensor [10,11]. However, they have used the thermopile with less sensitivity as a temperature sensor, and the floating thin film made of glass foil with relatively large dimensions of $10 \times 10 \times 0.07$ mm.

Eminoglu et al. have developed uncooled infrared micro-bolometer detector with a suspended pn junction diode as a temperature sensor. However, the diode is operated as a traditional thermo-diode with less temperature-sensitivity, which is based on the linear temperature dependence of forward voltage change for the constant current operation [14].

In this paper a new structural Pirani gauge-type thermal vacuum sensor combined with three pn junction diodes, operating under the constant forward voltage, as a high-sensitive temperature sensor working like a thermistor (we call this "diode-thermistor") and a MAB heater is proposed. It is demonstrated that this vacuum sensor has about two orders or wider sensitivity range (2×10^{-3}–1×10^{5} Pa) than that of the traditional Pirani vacuum sensor, and has very fast response and very low power consumption.

2. Experiments

2.1. Diode-thermistor and its characteristics

The author has proposed the very high-sensitive diode-thermistor acting as a variable sensitivity NTC thermistor [15–17]. The temperature sensitivity of this pn junction diode sensor can be adjusted by the forward bias-voltage, since the diode current I of this sensor has an exponential factor with respect to the reciprocal absolute temperature T at a constant bias-voltage V. This diode-thermistor is more sensitive and different from the usual diode temperature sensor based on the temperature dependence of the forward voltage change at the constant forward current.

Characteristics of this diode-thermistor are shown in Fig. 2.

For a given bias-voltage V of the pn-diode, the diode current I can be expressed by following equations:

$$\log I = -B\frac{1}{T} + C, \tag{2}$$

$$B = q\frac{(V_{\mathrm{d}} - V)}{nk}, \tag{3}$$

where q is electronic charge, V_{d} the diffusion potential, n the ideal factor of about 1, k the Boltzmann constant, C a constant determined by properties of Si material. B is an equivalent quantity to the thermistor constant.

2.2. Structure and working principle of this vacuum sensor

The author has proposed a new thermal conduction-type gas sensor using two temperature sensors and microheater formed together on the MAB, and this sensor is applied to the humidity sensor [17].

In this paper the sensor is applied to the thermal vacuum sensor. Two temperature sensors as a diode-thermistor, Th-A (diode A) and Th-B (diode B), are formed on separated but thermally connected region A and B, respectively, of a MAB (floating film). These regions A and B are thermally and weakly coupled by slit formed in the same MAB as shown in Fig. 3. The Th-A can measure the temperature T_{A} of the region A, in where the microheater is also formed, and can control the temperature of the microheater, and the Th-B formed in the region B can measure temperature T_{B}, which is sensitive to the pressure p. The ambient temperature T_{C} (corresponding to the room temperature) of the surrounding gas can be measured by the third diode-thermistor, Th-C, formed on the rim of the SOI substrate. The temperature T_{A} of the microheater is maintained to be constant such as $T_{\mathrm{A}} = T_{\mathrm{A1}}$ (such as 100 °C) by feedback control combined with the Th-A.

As mentioned above thermal vacuum sensor will be insensitive to the pressure p in the higher vacuum pressure range, such as 1 atm, from Eq. (1). However, in the pressure range below the point of mean free path l being on the order of the spacing between the microheater and heat sink, the thermal conductivity λ of the surrounding gas will depend on the molecular density n, namely, will be proportional to the pressure p [2]. Furthermore, in the extremely low vacuum pressure range this thermal sensor becomes insensitive to p, since the molecular density n itself