Available online at www.sciencedirect.com
SCIENCE DIRECT
Sensors and Actuators A 126 (2006) 300–305
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

A micro-Pirani vacuum gauge based on micro-hotplate technology

F.T. Zhang [a], Z. Tang [a,*], J. Yu [a], R.C. Jin [b]

[a] *Department of Electronic Engineering, Dalian University of Technology, Dalian, PR China*
[b] *Key laboratory of Microsystem and Micro-fabricating Technology, Dalian University of Technology, Dalian, PR China*

Received 14 April 2005; received in revised form 11 October 2005; accepted 19 October 2005
Available online 21 November 2005

Abstract

This paper presents a Pirani vacuum gauge based on a micro-hotplate (MHP) supported by six unequal beams. The MHP is fabricated using surface silicon micromachining technique. A thermal model for the gauge is established by means of Fourier analysis, which takes account of internal heat source in the beams and pressure-dependent gaseous heat conduction above and below the MHP. It is applied to determine the MHP operation temperature, temperature distributions along the supporting beams and heat losses through various mechanisms at different vacuum pressure. The measurements of gauge characteristics have been done and the results show good agreements with theoretical analysis. The measured sensitive range of the gauge is 10^{-1} to 10^{5} Pa when driven by a constant current, 0.8 mA.

Keywords: Micro-Pirani vacuum gauge; Micro-hotplate; Surface micromachining; Thermal sensor; Pressure sensor

1. Introduction

The Pirani vacuum gauge has been widely used in vacuum equipments. Traditional Pirani structure usually consists of a heated cylindrical wire with high temperature coefficient of resistance (TCR) and large dimensions [1]. In recent years, solid micro-Piranis are studied in the wake of developments in microelectronics and micromachining [2–5]. These micro-Piranis can provide not only a wider measurement range and better sensitivity with lower power consumption but also an excellent manufacturing yield [6,7].

Among various micro-Paranis, surface micromachined ones usually use a suspended structure with thin air-gap, large membrane, and long and narrow supporting beams to heighten their performances [4,5]. Stress and mechanical strength controlling, however, are always accompanying problems under the optimal goals of lower power consumption, higher sensitivity, and wider measurement range. In this study, a novel structure based on micro-hotplate (MHP) technology is fabricated. Besides traditional four supporting beams, two additional narrow and short ones with low thermal conduction are used in the structure. They can strengthen mechanical support so that the other four beams can be longer to reduce total solid heat conduction efficiently and achieve a lower limit of detectable pressure range. Meanwhile, a thermal model is built to analyze the structure and focus is put on the temperature grad and heat losses of the beams by taking into account of internal heat source in the beams and pressure-dependent gaseous heat conduction above and below the MHP, which are critical for the surface-machined membrane with long beams but usually ignored in the previous studies.

2. Thermal characteristic analysis of the micro-Pirani structure

The top and the cross-section views of the MHP-based micro-Pirani are shown in Fig. 1. This MHP is supported with four long beams as well as two short and narrow ones. The pressure-dependent voltage across the square membrane is measured with four-point method. Beam 3 and its diagonal one lead the heating resistor, which is driven by a constant current circuit for elevating the MHP up to its operation temperature. For this reason, these two beams should be considered as models with internal heat source for thermal analysis. Whereas, for the other two long beams with measurement leads connected to the heater and the two short beams, internal heat source is negligible because no or only very low current passes through them.

* Corresponding author. Tel.: +86 411 84707945; fax: +86 411 84708918.
E-mail address: tangza@dlut.edu.cn (Z. Tang).

0924-4247/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2005.10.016

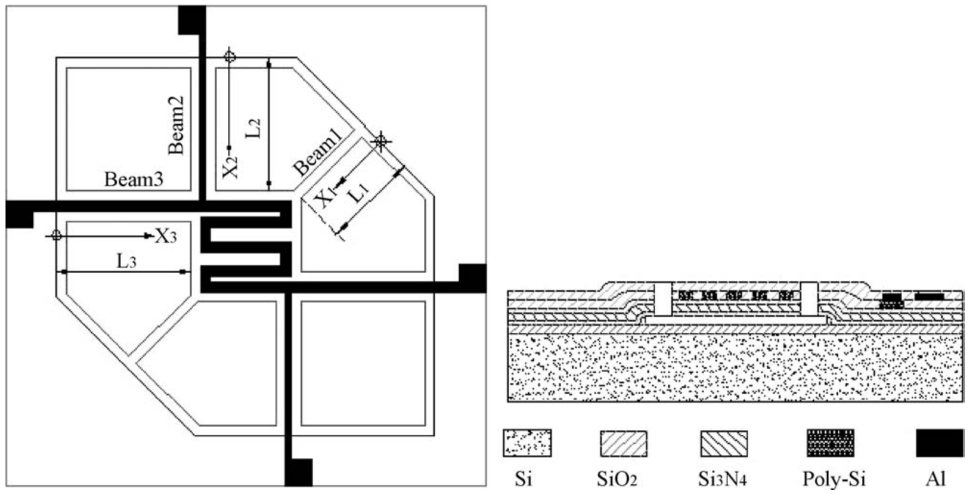

Fig. 1. The top and the cross-section views of the designed sensor.

Electrical power (P) in the square membrane can be dissipated by the following heat loss mechanisms: solid thermal conduction through the supporting beams (Q_s), gaseous 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 in micro-Piranis, the last two ones can always be neglected. Therefore, P can be simply described as follows

$$P = U_a \times I = I^2 \times R_a = Q_s + Q_g \tag{1}$$

where R_a and U_a are the resistance of heating segment in the square membrane and the corresponding voltage drop across it, respectively. I is the heating current.

To evaluate the MHP operation temperature, the following assumptions are made for simplicity. First, the temperature distributions in the square membrane and along its vertical direction are uniform with the same temperature T_s. Next, the temperature distributions in any cross-section of the beams are uniform and are functions of the distance x_j ($j = 1, 2, 3$) from the anchorage ends. Additionally, temperatures of these anchorage ends and the bottom substrate below hotplate are set at ambient temperature, T_a.

According to Fourier law, Eq. (1) can be rewritten as

$$I^2 R_{a0}[1 + \alpha(T_s - T_a)] = G_g(T_s - T_a) + 2\sum_{j=1}^{3} \kappa_j \frac{dT(x_j)}{dx_j}\Big|_{x_j = L_j} \tag{2}$$

where R_{a0} is the initial value of R_a at T_a K, which can be measured with the method discussed later. α is TCR of the heater and measured to be 0.091%/K for the doped polysilicon resistor. G_g is the gaseous thermal conductance. $j = 1$, 2 and 3 correspond to beam 1, beam 2 and beam 3, respectively. $T(x_j)$ represents the temperature distribution in beam j. κ_j is defined as $\kappa_j = \lambda_j A_{bj}$. λ_j is the equivalent solid thermal conductivity of beam j and determined by the thermal conductivities and cross-section areas of the constitutive thin film layers. A_{bj} and L_j are the total cross-section area and length of beam j. Two is multiplied before sigma (Σ) for the symmetrical geometry. So the two terms on the right are the heat losses of the square membrane through gaseous heat conduction (Q_g) and solid heat conduction (Q_s), respectively.

For the mechanism of pressure-dependent gaseous heat conduction, thermal conductance has been proven previously as [7]

$$G_g = \frac{\varphi}{2 - \varphi} G_a A_s P \left(\frac{P_{td}}{P + P_{td}} + \frac{P_{tu}}{P + P_{tu}} \right) \tag{3a}$$

and

$$G_a = \Lambda_0 \left(\frac{273.2}{T_a} \right)^{1/2} \tag{3b}$$

where P is the gas pressure; P_{td} and P_{tu} are the transition pressures on two sides of MHP, which are inversely proportional to the air gaps below or above the MHP, respectively; φ is the accommodation coefficient of gas; G_a, Λ_0 are the free molecular conductivities at T_a and at 273 K, respectively; and A_s is the square membrane area.

From Eq. (2), the temperature distributions of the beams have to be determined firstly to obtain Q_s. According to Fourier analysis, the temperature distribution $T(x_j)$ in beam j satisfies the following differential equation

$$\lambda_j \frac{d^2 T(x_j)}{dx_j^2} = -\frac{I^2 \rho_a}{A_h A_{bj}}[1 + \alpha(T(x_j) - T_a)] + \frac{G_g}{A_s t_b}[T(x_j) - T_a] \tag{4}$$

where ρ_a, A_h denote the resistivity and cross-section area of the heater. ρ_a is the sheet resistance multiplied by its thickness at ambient temperature. t_b is the MHP thickness. The first term on the right is the heat generation density, the second corresponds to the loss due to the thermal flux across the air gap. The first term should be omitted because no currents pass on the beams when $j = 1, 2$.

The boundary conditions satisfied by the solutions of Eq. (4) are

$$T(x_j)|_{x_j=0} = T_a \tag{5}$$