Sensors and Actuators A 161 (2010) 108–113

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A micro-machined Pirani gauge for vacuum measurement of ultra-small sized vacuum packaging

Xuefang Wang [a,c], Chuan Liu [b], Zhuo Zhang [a,c], Sheng Liu [a,c], Xiaobing Luo [b,c,*]

[a] School of Mechanical Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[c] MOEMS Division, Wuhan National Lab for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 8 December 2009
Received in revised form 30 April 2010
Accepted 30 April 2010
Available online 7 May 2010

Keywords:
Wafer level
Vacuum packaging
Pirani gauge
Vacuum monitor

ABSTRACT

Quite a few MEMS devices need vacuum packaging technology to guarantee the desirable performance. Developing an absolute vacuum environment for those devices is indispensable. However, it is difficult to monitor the pressure change in vacuum chamber in on-line and real-time mode. A surface micro-machined Pirani gauge for measuring vacuum pressure inside vacuum packaging in wafer level was presented in this paper. It was designed with a simplified structure and did not need complex circuit. Only a simple Wheatstone bridge circuit is needed, which could be manufactured by conventional CMOS processes. Preliminary tests on this device were conducted. The experimental results show that the Pirani gauge is capable of measuring pressures from atmospheric value to 1 Pa and has a very good linearity in the range from1 Pa to 300 Pa. It demonstrates that the micro-machined Pirani gauge has great potential to be used in wafer level vacuum packaging. Also, the Pirani gauge is able to be the packaging hermeticity detector.

1. Introduction

In recent years, numerous devices require vacuum packaging for optimal operation [1], such as MEMS gyroscope sensors, micro-filters, MEMS ultrasonic sensors [2,3], high-end micro-accelerometers [4,5] and so on. These devices need vacuum environments to reduce the gas damping of the mechanical moving parts, which will improve the device quality factor, enhance their performances, and greatly reduce the energy consumption of the whole microsystem.

Existing methods for vacuum measurement in MEMS devices include helium leak testing and Q factor extraction [6,7]. Helium leak testing needs expensive equipment (~$15,000) and is generally limited to the application situations where the leak rates are greater than $10^{-12}\,\mathrm{cm^3/s}$ [1]. The above factor results in high cost and cannot perform on-line and real-time pressure change observation in vacuum cavity for helium leak testing. Q factor measurements are limited by complicated circuits and not sufficient sensitivity at the level of low pressures [8,9], thus, it cannot precisely measure small pressure change inside a sealed micro-cavity [10]. Our group reported on-line monitoring method using embedded resonator [11,12]. However, for these sensors, their fabrications are complicated and expensive, and they are proved to have low pressure sensitivity under 10 Pa.

So far, numerous miniaturized Pirani gauges have been reported due to the development of micro-machining technology [13,14], which can utilize simple front-surface-etching technique and provides wide and linear response [15]. In addition to these devices, a new surface micro-machined Pirani pressure sensor with an extremely narrow gap between heater and heatsink (substrate) was also designed and fabricated in reference [16].

In this paper, a low cost and high sensitivity micro-machined vacuum gauge – Pirani gauge – was presented, which is suspended by a thin membrane structure, with a groove cavity etched on the substrate. The heater material is Pt, it has good linearity and stability. Compared with traditional structure of four supporting beams, the present structure provides not only low thermal loss through leads to the substrate and large active area for gaseous heat conduction, but also can strengthen mechanical support for the Pirani vacuum sensor. Meanwhile, it can be integrated with general micro-packaging technologies. Experimental tests on this Pirani gauge were conducted. The experimental results show that this Pirani gauge is capable of measuring a range of pressures linearly from atmospheric to 1 Pa and has a very good linearity especially in the range of 1–300 Pa.

* Corresponding author at: School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China.
E-mail address: Luoxb@mail.hust.edu.cn (X. Luo).

0924-4247/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2010.04.034

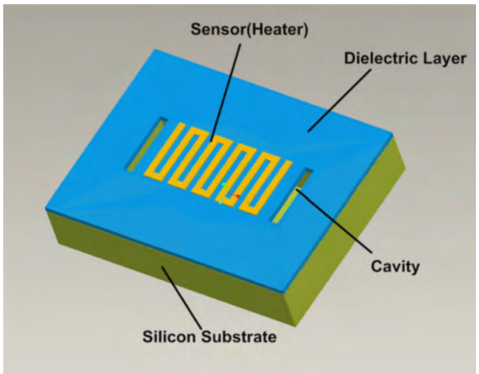

Fig. 1. Device structure of micro-Pirani sensor.

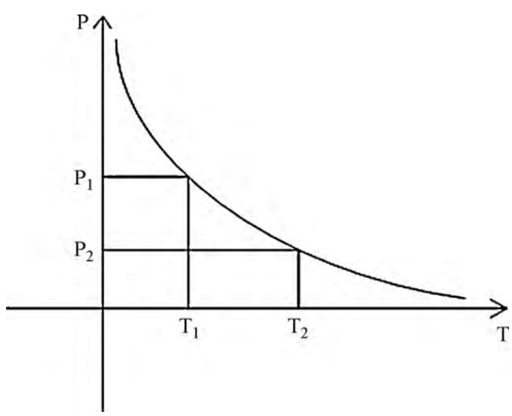

Fig. 2. Profile of vacuum chamber's pressure versus temperature.

2. Device structure and operation principle

Fig. 1 shows the device structure of the present micro-Pirani sensor. It includes a cavity, an insulating layer locally positioned on the cavity and the sensor deposited on the insulating layer such that the air moves across the sensors by virtue of free convection. The sensor acts as the heater during operation.

Pirani gauge's working principle is based on the fact that heat loss of a hot plate to its ambient through gas conduction is proportional to the molecular density of gas in the vacuum system [17]. The vacuum pressure can be measured in terms of the temperature changes of the platinum film sensitive resistor, which is reflected accurately by the amount of heat loss. The device is packaged in a sealed vacuum chamber. When the sensor is provided with a current, its temperature rises, then the air around it is heated, free convection is established in the cavity. The output current changes as temperature changes, by measuring the current difference, the pressure of the vacuum chamber can be acquired.

Fig. 2 shows the profile of the vacuum chamber's pressure versus temperature. From the figure it can be seen that the temperature of the platinum film sensitive resistor changes at the same time when the vacuum pressure of the vacuum chamber changes. Thus the resistance changes with the changed temperature, the vacuum pressure can be obtained through measuring the output voltage.

3. Design

The input power to the MEMS Pirani sensor is equal to the heat loss of heater to its ambient, the main heat transfer includes solid conduction, gas conduction, and thermal radiation. The magnitude of each term depends on the structure and the ambient conditions.

For pressure measurement, the major contributions come from the term of the gaseous conduction, which can be expressed as [15,17]

$$G_g = \frac{\varphi}{2-\varphi} G_a A_s P \left(\frac{P_{t1}}{P + P_{t1}} + \frac{P_{t2}}{P + P_{t2}} \right) \tag{1a}$$

and

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

where φ is the accommodation coefficient of gas; G_a and Λ_0 are the free molecular conductivities at T_a and at 273 K, respectively; As is the floating plate area; P is the ambient pressure; P_{t1} and P_{t2} are transition pressures on both sides of the membrane, which are inversely proportional to the effective separations of the membrane from their heat sinks [17].

For the thermal conduction of the present device, it can be assumed that the temperature distribution is mainly determined by the contact area of heated film and the insulating layer, the physical and geometric properties of the insulating layer. An empirical formula for the thermal conduction of the device was reported previously by Weng and Shie [15], which is written as

$$G_s = \left(\frac{1}{4.2 k_t d} \frac{B}{A} + 5 \times 10^4 \right)^{-1} \tag{2}$$

where k_t is the thermal conductivity (W/cm °C), d is the effective thickness of the glass with its Pt-coated film. The first term on the right-hand side of Eq. (2) is the thermal resistance of the leads. The second term represents the spreading resistance on the membrane area. In the design, the membrane is treated as uniform material having an equivalent thermal conductivity of 0.0312 W/cm °C and an equivalent thickness of 250 nm. Here A = 100 μm and B = 477 μm. Conductivity of the platinum film is estimated from its bulk value. Real conductivity, however, is generally lower due to the effect of surface scattering of thin films [15].

Regarding to the radiation heat transfer of a floating membrane, the Stefan–Boltzmann law is used, which results in the following equation [15,18]:

$$G_r = 2\varepsilon\sigma A_s \left(T^2 + T_a^2 \right) (T + T_a) \tag{3}$$

where ε is the emissivity, A_s is the floating plate area, and σ is the Stefan–Boltzmann constant.

From the above analysis it is known that the increasing of the gas convection heat transfer and reducing thermal conduction can increase the sensitivity and the dynamic range of the Pirani gauge. In this paper, we used two measures to realize the above target, the first is that a groove cavity is etched in the substrate to reduce the contact area of the dielectric layer with the substrate, the second is to reduce the thickness of dielectric layer and choose some insulation materials with small thermal conductivity.

Using Eqs. (1)–(3), we have designed numerous dimensions to try to achieve the best performance. Every dimension can use the above equations to calculate, and by comparing the results of thermal distribution at different designs, we can get the optimum dimensions.

Fig. 3 shows the calculation results of the thermal conductance for one design. In Fig. 3, the total thermal conductance, G_t, is the sum of the above three quantities in Eqs. (1)–(3). Λ_0 is 0.0164 W/cm^2 °C, and the parameters φ, P_{t1} and P_{t2} are 0.9, 19.72, and 1.12 [15]. When the air pressure is larger than 100 Torr, G_g is approximately four times of G_s, and is nearly saturated. G_g decreases linearly with the vacuum pressure when it is smaller than 10 Torr. The radiative conductance of the device shown here is obtained by assuming that the temperature rise of the plateau is 100 °C or more at zero-pressure condition for the ambient. It decreases slightly in the high-pressure regime.