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A single crystal silicon micro-Pirani vacuum gauge with high aspect ratio structure

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ABSTRACT

This paper presents a very simple micro-Pirani vacuum gauge made of single crystal silicon. It was fabricated by conventional bulk micromachining technology with only three masks. The gauge has 80 μm thick bulk silicon as structure layer and dual heat sinks, which is very robust with very little internal stress and also provide large heat transfer area. Highly phosphorus ion doping at bottom of the anchors forms ohmic contact with Cr/Au leads. *I–V* curve shows good linear resistance characteristic of the single crystal silicon heater. The dynamic range of the Pirani vacuum gauge is 1–1000 Pa, and the average sensitivity in the dynamic range is 117 K/W/Pa. With an uncertainty of 1%, the resolution of the gauge is 12 Pa at 1000 Pa and 0.2 Pa at 4 Pa.

1. Introduction

The Pirani vacuum gauges have been widely used in vacuum equipments for pressure measurement from 1 Pa to 10^5 Pa. Using micromachining technology, researchers have developed various micro-Pirani vacuum gauges, which provide large measurement range and high sensitivity with low power consumption. Micro-Pirani vacuum gauges also can be easily integrated into hermetically sealed vacuum packages of microelectromechanical systems (MEMS) for in situ pressure measurement [1]. Compared to other methods for vacuum measurement of micro-packages, such as helium leakage test and Q factor extraction, Pirani vacuum gauges are low-cost and easy to operate with high sensitivity for long term monitoring.

There are approximately three types of micromachined Pirani vacuum gauges. The first group is micro-hotplate using deposited metal or poly-silicon thin film on dielectric membrane as hotplate and the substrate as the heat sink [2–7]. The dielectric membrane provides mechanical support for the metal/poly-silicon resistor. However, the stress of the membrane must be considered to achieve narrower air gap for increasing dynamic range [6]. The second group is microbridge used as the heater and the substrate as heat sink [8–10]. It is easy to fabricate and compatible with many MEMS devices fabrication. However, in order to measure low pressures, long and thin microbridges are needed, so the buckling problem must be considered. The third group is micro-sink which has a structure of lateral heat transfer with dual heat sinks [11,12]. Based on this structure, Pirani vacuum gauges fabricated by dissolved wafer process (DWP) and silicon-on-glass (SOG) processes have been presented. Theses processes were totally compatible with the fabrication of those thick structure MEMS devices.

In this paper, we present a single crystal micro-Pirani vacuum gauge fabricated by bulk micromachining technology using the lateral heat transfer structure with dual heat sinks. This gauge has 80 μm thick bulk silicon as structure layer with good mechanical and thermal stability. Low resistivity (0.01–0.03 Ω cm) silicon wafer is used to provide better electrical conductance as the resistive heater. The bottom of the anchor was highly doped through ion implantation to form good ohmic contact. The fabrication process is very simple with only three masks. High aspect ratio structure with dual heat sinks largely increases the effective heat transfer area and so the performance of the gauges. The basic properties, such as direct-current characteristics, contact resistance and the temperature dependent resistance of the gauge, were elaborately studied. The performance of the gauge was measured at last.

2. Design and consideration

The principle of Pirani vacuum gauge is that the heat conduction through gas between the heater and heat sink is proportional to pressure at low pressure. The total heat conduction from heater to ambient has three parts: thermal conductance through solid contacts G_{Solid}, thermal conductance of gas between heater and heat sink G_{Gas}, and radiation $G_{Radiation}$. So, the total thermal conductance

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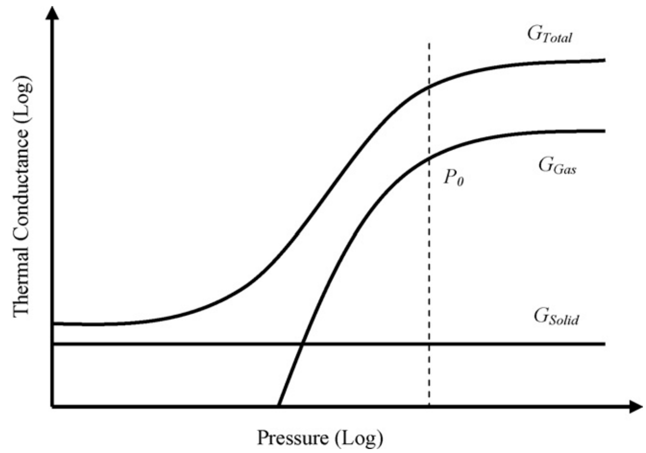

Fig. 1. Thermal conductances of gas, solid and total versus pressure.

of the gauge is [13]:

$$G_{Total} = G_{Solid} + G_{Gas} + G_{Radiation} \tag{1}$$

The radiation can be neglected at low temperature. As shown in Fig. 1, solid thermal conductance can be considered to be constant and gas thermal conductance is dependent on pressure, which can be modeled as [13]:

$$G_{Gas}(P) = G_{Gas}(\infty)\frac{P/P_0}{1+P/P_0} \tag{2}$$

where P is pressure, P_0 is the empirical transition parameter, which is reciprocal of the gas gap, and $G_{Gas}(\infty)$ is the gas thermal conductance at atmosphere pressure.

Narrower gap will push the transition pressure P_0 to higher pressure, which significantly increases the upper limit of dynamic range [11]. The lower limit of dynamic range is determined by $G_{Solid}/(G_{Gas}+G_{Solid})$. G_{Gas} decreases quickly at low pressure so that G_{Solid} becomes the primary factor. The lateral heat transfer structure with dual heat sinks and the high aspect ratio of the device can enlarge the heat transfer area through gas gap, and then extend the lower limit of dynamic range [11]. The lateral structure with dual heat sinks has been demonstrated to have higher sensitivity than conventional single heat sink structure [11]. As the analysis in the literature [12], decreasing the width and the height and increasing the length of the heater increase the sensitivity of the gauge.

Because single crystal silicon has relatively large Young's Modulus (165 GPa) and bulk silicon structure has no internal stress, the micro-Pirani vacuum gauge with high aspect ratio structure has very good mechanical rigidity. This enables long heater design, which can extend the low limit of dynamic range and increases the sensitivity of the device. The thermal property is also very stable of the material. Fig. 2 shows the schematic graph of our micro-Pirani

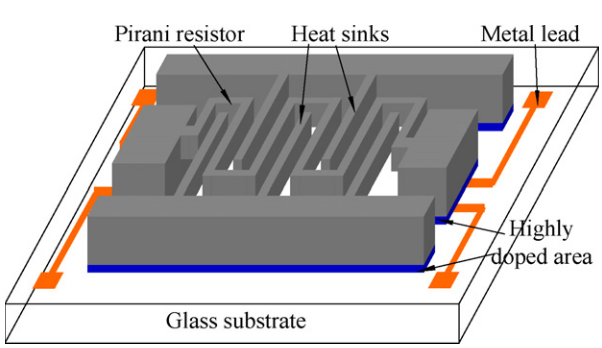

Fig. 2. The schematic graph of the single crystal silicon Pirani vacuum gauge.

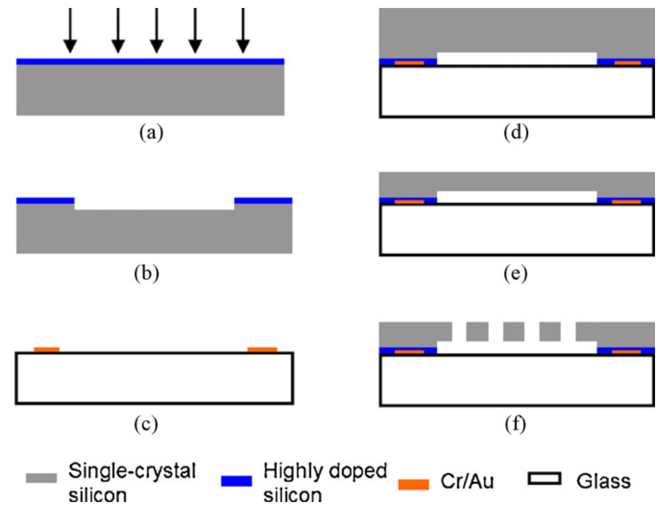

Fig. 3. The process flow of the micro-Pirani vacuum gauge.

vacuum gauge. The bottom of the anchors has been highly doped to form ohmic contact with the metal leads. The folded heater is suspended between two anchors with heat sinks overlapped at both sides. The total length of the folded heater is 33.53 mm. The widths of both the heater and heat sinks are 25 μm. The thickness of the gauge is 80 μm. The gap between the heater and heat sinks is 5 μm. For a 2.4 mm^2 die area, the total effective lateral heat transfer area is 5.36 mm^2.

3. Fabrication

The micro-Pirani vacuum gauge was fabricated by commonly used bulk micromachining technology with silicon-on-glass (SOG) structure. Fig. 3 shows the process flow. The process started with phosphorus ion implantation with a dose of $6 \times 10^{15}\,cm^{-2}$ and energy of 80 keV to the silicon wafer (Fig. 3(a)). Afterwards the wafer was annealed in 1000 °C for 30 min. The sheet resistance after implantation and annealing is 0.2–0.3 Ω/□. Then 10-μm depth trenches of the silicon wafer were defined by Deep Reactive Ion Etching (DRIE) process (Fig. 3(b)). The 20 nm/130 nm thick Cr/Au was sputtered on the Pyrex 7740 glass wafer and patterned by lithography and lift-off technique to form the leads (Fig. 3(c)). Then the silicon wafer was anodically bonded to the glass substrate (Fig. 3(d)). The silicon wafer was thinned by KOH wet-etching to 90 μm left (Fig. 3(e)). Finally, the heater and the overlap heat sinks were released by DRIE (Fig. 3(f)). The whole process only needs three masks and is compatible with the fabrication of most thick structure MEMS devices. Fig. 4 is the SEM photos of the gauge. The device has good plane structure without any buckling.

4. Measurement

The micro-Pirani vacuum gauge was characterized by extracting the thermal impedance ($R_{thermal} = \Delta T/\Delta P$) at different pressures. Four-probe method was used for accurate resistance measurement. When a constant current I was applied to the heater across two leads, the voltage drop V was measured across the other two. When the gauge got to a thermal and electrical balance at that current, the resistance of the heater R was determined by V/I. Referred to the relationship of resistance and temperature, the average temperature of the heater T was obtained. The joule heating power P was calculated by $V \cdot I$. At a certain pressure, the thermal impedance was extracted as the slope of the linearly fitted curve of the temperature versus heating power.