Silicon on insulator temperature and pressure sensor for MEMS smart packaging

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Abstract

This paper presents hermetic packaging for MEMS with integrated temperature and pressure sensors based on Silicon On Insulator technology. Temperature and pressure are measured with a single device composed of an aluminium resistor on a suspended silicon membrane. Temperature is determined with the variation of the electrical conductivity of aluminium, whereas the absolute gas pressure measurement is based on the Pirani gauge principle. Design, simulation and experimental characteristics of the sensor confirm the feasibility of this multipurpose sensor approach. The proposed hermetic packaging process enables the electrical contacts to cross the hermetic cavity without need of vias.

Keywords: Temperature sensor; Pressure sensor; Pirani gauge; MEMS Packaging; Eutectic bonding

1. Introduction

Industrial integration of MEMS in the electronic systems becomes more usual because of their maturity and of their cost reduction. The assembly operations of these components remain critical because they are sensitive to the environmental conditions such as pressure variations 1,2. For several applications, MEMS must be kept in vacuum, but such packaging is not easy to perform and only few control methods are developed 3,4. This work investigates solutions to address this problem using the so called “smart packaging” approach: sensors are included in the package for in-situ measurements of the physical parameters inside of the MEMS hermetic cavity 5,6. The sensors are designed using a multipurpose approach in order to reduce their overall size and the number of electrical connections.

2. Sensors design, modeling and characterization

The sensor structure is based on an aluminium resistor deposited onto a silicon suspended membrane schematically represented on Fig. 1. The sensor enables both for ambient temperature and pressure measurements,
deducted from the resistance of the aluminium resistor $R$, whose value depends on temperature $T$, the reference value $R_0$ at the reference temperature $T_0$ and the temperature coefficient of resistivity (TCR) of aluminium $\alpha$

$$R(T) = R_0(1 + \alpha \cdot (T - T_0))$$

(1)

The resistor is measured with the four-point method: beams 1 and 3 lead the current, whereas beams 2 and 4 are used for voltage measurement. In the first configuration, the current is very weak and the heating of the resistor and the membrane remains negligible, so the resistance value is representative of the ambient temperature $T_A$. Conversely, in the second configuration high current value is used to induce significant joule heating of the resistor and the suspended membrane. Gas pressure is then determined through the Pirani gauge principle. This principle lies on pressure dependence of the thermal conductivity of gases. Former works\textsuperscript{7,8} showed that gases thermal conductivity $\lambda_G$ varies as a function of the pressure $P$ according to the following empiric law

$$\lambda_G = \frac{P \lambda_{G0}}{P + P_{tr}}$$

(2)

where $\lambda_{G0}$ is the gas thermal conductivity for “high” pressures, and $P_{tr}$ represents the transition pressure. This parameter is inversely proportional to the gap distance $t_G$ between the hot membrane and the substrate.

Due to moderate operating temperature of the sensor and its small dimensions, solid thermal conduction and gaseous conduction only are considered as dissipation modes. To simplify analytical expressions, the temperature is assumed to be uniform with the same value $T_H$ in the square membrane, and the anchorages ends of the beams are supposed to be at the ambient temperature $T_A$. According to Fourier Law, the power balance can be expressed as

$$R_0(1 + \alpha \cdot (T_H - T_0)) \cdot I^2 = \sum_j \frac{\lambda_A A_B}{t_B} (T_H - T_A) + \frac{\lambda_G A_G}{t_G} \frac{dT(x_j)}{dx_j} \bigg|_{x_j = L}$$

(2)

where $I$ is the current passing through the resistor and $j$ is the beams number. $A_M$, $A_B$, $L$ and $\lambda_B$ are respectively the square membrane area, the beams cross-section area, their length and their thermal conductivity. Calculation of the temperature along the beams is based on solid heat conduction into the beams and heat conduction through gas between the beams and the substrate. Beams 1 and 3 are considered with internal heating sources due to the current $I$ across the aluminium film, whereas beams 2 and 4 have no internal heating source ($I=0$). General expression of the temperature profile of the beams satisfies the following differential equation

$$\rho B \frac{d^2 T(x_j)}{dx_j^2} + \frac{\lambda_B I^2}{A_M A_B} \left[ 1 + \alpha \cdot (T(x_j) - T_0) \right] = \frac{\lambda_G}{t_B} \frac{dT(x_j)}{dx_j} \bigg|_{x_j = L}$$

(3)

where $\rho_B$, $A_M$ and $t_B$ are respectively the aluminium resistivity, the aluminium track cross-section area and the beams thickness. The solution of this equation enables to determine the expression (4) of $dT(x_j)/dx_j$ for $x_j = L$ of each beam. The square membrane temperature $T_H$ can be then calculated by substitution of (4) into (2).

$$\frac{dT(x_j)}{dx_j} \bigg|_{x_j = L} = K_1 (1 - \cosh(K_2 L)) + \frac{K_2}{\tanh(K_2 L)} (T_H - T_A)$$

(4)
with \[ K_1 = \frac{\rho_0 l^2}{\lambda_B A_B A_L} (1 + \alpha (T_A - T_0)) \] and \[ K_2^2 = \frac{\lambda_A}{\lambda_B} \frac{A_B}{A_L} \frac{1 + \alpha_0 l^2}{1 + \alpha l^2} \]

Thermal behavior of three different sensor designs is simulated. The sensors are all based on SOI technology, with 5 μm silicon, 2 μm silicon dioxide thicknesses (i.e. \( t_S = 5 \mu m \) and \( t_G = 2 \mu m \)) and 400 μm silicon substrate. The aluminum track thickness is 500 nm, so the beams total thickness is \( t_B = 5.5 \mu m \). The beams and the aluminium tracks are 10 μm width. The sensors have the same 100 μm x 100 μm square membrane. The only design difference concerns the beam lengths \( L \), which are 100 μm, 250 μm and 600 μm for the designs type 1, type 2 and type 3 respectively. Fig. 2 shows that heating of the membrane remain negligible for 1 mA and lower currents. These simulations also show that the sensors with long beams are more efficiently heated. Indeed, solid thermal conduction is weaker in this case. And the membrane temperature is also more influenced by the gas pressure because heat dissipation by the gaseous conduction mode is more important in this case.

![Fig. 2. Temperature difference \( T_H - T_A \) at 1000 mbar and at \( 10^{-3} \) mbar (a) device type 1; (b) device type 2; (c) device type 3.](image)

The temperature/pressure sensors represented on Fig. 3 were elaborated using the process described in the following section. Characterization as temperature sensor was performed at 1 mA current. Measurements in the range of 270 to 350 K using a Peltier temperature controller show very good resistance linearity as a function of temperature (Fig. 4 (a)). The TCR of the aluminium film was determined to be 0.32% K\(^{-1}\). Characterization as pressure sensor was performed at 35 mA current. Simulation and experimental results presented in Fig. 4 (b) shows that sensitivity of the sensor type 3 is much more important than that of the two others.

![Fig. 3. SEM pictures of the three sensors’ structures (a) type 1; (b) type 2; (c) type 3.](image)

![Fig. 4. (a) Resistance relative variation vs. temperature (1mA current); (b) relative resistance variation vs. gas pressure (35 mA current).](image)
3. Smart package fabrication process

Main steps of the fabrication process are represented in Fig. 5. The sensors presented on Fig. 3 were elaborated using steps (a), (b), (c) and (f). The smart package including the sensor is hermetically sealed using Au/Si eutectic bonding. Peculiarity of the process is that the sensor electrical connections cross the hermetically sealed cavity without using via technology. This technique is also usable for the MEMS electrical connections. Experimental validation of the overall packaging process is currently in progress.

Fig. 5. (a) Holes etching of Si top layer; (b) Al film deposition and resistor patterning; (c) Si Membrane patterning; (d) Backside holes etching; (e) Backside Al contacts deposition; (f) Si membrane release (HF vapour); (g) Au/Si eutectic bonding of the smart package onto the MEMS.

4. Conclusion

Simulations and experimental results show that both temperature and pressure can be measured using a single sensor with two different measurement configurations, introducing the concept of multipurpose sensor. This approach is an efficient way to reduce the size and the number of electrical connections of the sensors embedded into the smart packaging. Current work aims at validating the proposed sealing process of the smart packaging, whose main interest is to achieve electrical connections across the hermetic packaging without using the technology of via, which may cause leakage problems.

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