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Sensitivity analysis of packaging effect of silicon-based piezoresistive pressure sensor

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ABSTRACT

The silicon-based pressure sensor is one of the major applications in the MEMS device. Nowadays, the silicon piezoresistive pressure sensor is a mature technology in the industry, but its requirement in terms of sensing accuracy and stability is more rigorous than that of many advanced applications. The major factor affecting the sensing stability of the piezoresistive pressure sensor is its thermal and packing effects. For a packaged pressure sensor, silicone gel is usually used to protect the die surface, so the thermal and packaging effects caused by the silicone gel should be taken into consideration to obtain better sensing sensitivity and stability. For fast design and optimization purpose, a finite element method (FEM) is adopted for sensor performance evaluation, packaging-induced signal variation, and thermal/packaging effects will be examined in this research. Several experiments are also performed to validate the finite element model. After the simulation is validated, an optimization analysis is carried out under different packaged pressure sensor design parameters. The simulation results show that the different geometry of the protection gel will influence pressure sensitivity significantly; base on analysis results, this research will conclude a design guideline for pressure sensor packages with concave and convex type of protection gel.

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1. Introduction

Since the piezoresistive effect was discovered, the applications of piezoresistive sensors have been widely employed in mechanical signal sensing. The fundamental concept of the piezoresistive effect is the change in resistivity of a material resulting from an applied loading. This effect in silicon material was first discovered by Smith [1] in the 1950s and has been applied extensively in mechanical signal measurement for years. Smith proposed the change in conductivity under stress in bulk *n*-type material and designed an experiment to measure the longitudinal as well as transverse piezoresistance coefficients. Pfann et al. [2] presented the shear piezoresistance effect; they designed several types of semiconductor stress gauges to measure longitudinal, transverse, and shear stresses and torque. In addition, a Wheastone bridge type gauge in mechanical signal measurement is employed. On the other hand, piezoresistance coefficient is a function of impurity concentration and temperature; hence the thermal effect will influence the measurement result of a piezoresistive sensor. Piezoresistive pressure sensor design was widely studied in the 1990s in the MEMS and electronic packaging fields. Jaeger et al. [3,4] employed piezoresistive sensors made on silicon chips to measure the stresses within electronic packaging devices. Kanda [5] applied the MEMS process to fabricate piezoresistive pressure sensors on {1 0 0} and {1 1 0} wafers for optimum design considerations. Recently, the FEM has been widely adopted for stress prediction, thermal effect reduction, packaging design and reliability enhancement of piezoresistive sensors. Pancewicz et al. [6] used FEM to obtain the output voltage of the pressure sensor, and compared the simulation data with experimental results. Schilling et al. [7] also applied FEM analysis for sensor performance simulation and discussed the packaging effects on the silicon piezoresistive pressure sensors. Moreover, Peng et al. [8,9] used FEM demonstrated a promising result for the prediction of sensor performance. For the application of FEM in the optimum design of the pressure sensor, Krondorfer et al. [10] used FEM software to predict thermal effect resulting from the fabrication processes of pressure sensor packaging.

To operate the piezoresistive pressure sensor in a harsh environment, silicone gel is usually required to protect the die surface. However, some design parameters such as silicone gel that will affect sensor sensitivity and stability were not discussed in previous research. For this reason, the material and geometry of silicone gel are considered in this study to investigate thermal and packaging effects. Furthermore, to achieve better sensor performance, FEM parametric and factorial design analysis is performed. The design

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Table 1
The ANOVA table for the two-factorial, fixed effects model.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F statistic
A	SS_A	$a-1$	$MS_A = \frac{SS_A}{a-1}$	$F_A = \frac{MS_A}{MS_E}$
B	SS_B	$b-1$	$MS_B = \frac{SS_B}{b-1}$	$F_B = \frac{MS_B}{MS_E}$
AB	SS_{AB}	$(a-1)(b-1)$	$MS_{AB} = \frac{SS_{AB}}{(a-1)(b-1)}$	$F_{AB} = \frac{MS_{AB}}{MS_E}$
Error	SS_E	$ab(n-1)$	$MS_E = \frac{SS_E}{ab(n-1)}$	–
Total	SS_T	$abn-1$	–	–

Table 2
Dimensions of Silicone Gel, PCB, glass, adhesive layer, silicon chip and silicon membrane.

Layer	Length (μm)	Width (μm)	Thickness (μm)
Silicon membrane	600	600	20
Silicon chip	1600	1600	420
Glass	1600	1600	580
Adhesive	1600	1600	50
PCB	10000	10000	1200
Silicone gel	4000	4000	150

parameters include silicon chip length and thickness, membrane length, silicone gel thickness and material, and so on.

2. Fundamental theory

2.1. Fundamental theory of piezoresistive pressure sensor

For a membrane type piezoresistance pressure sensor, the stress state on the resistors can be assumed to be plane stress condition ($\sigma_z = \sigma_{xz} = \sigma_{yz} = 0$) and the shear stress σ_{xy} which is much small than the normal stress σ_x and σ_y. The two uniaxial stresses for the membrane type piezoresistance sensor are longitudinal stress σ_l (electric field and current of this piezoresistor are in the same direction) and transverse stress σ_t (which is perpendicular to the direction of the electric field and current). The relationship between resistivity variations and stress changes can be expressed as follows:

$$\frac{\Delta\rho}{\rho} = \pi_l\sigma_l + \pi_t\sigma_t \quad (1)$$

$$\pi_l = \pi'_{11} = \pi_{11} + 2(\pi_{44} + \pi_{12} - \pi_{11})({l_1}^2{m_1}^2 + {l_1}^2{n_1}^2 + {m_1}^2{n_1}^2) \quad (2)$$

$$\pi_t = \pi'_{12} = \pi_{12} - (\pi_{44} + \pi_{12} - \pi_{11})({l_1}^2{l_2}^2 + {m_1}^2{m_2}^2 + {n_1}^2{n_2}^2) \quad (3)$$

In Eqs. (2) and (3), π_l is the longitudinal piezoresistance coefficient, π_t is the transverse piezoresistance coefficient, and π_{ij} are the piezoresistance coefficients defined as a 6 × 6 matrix. For the cubic crystal structure of silicon, the coefficients of matrix can be reduced to three independent components, which are π_{11}, π_{12}, and π_{44}. In addition, the symbols l, m and n are the direction cosines between the ⟨1 0 0⟩ axis and a given crystal direction. On the other hand, the piezoresistors on the membrane are connected in a Wheatstone-bridge. Therefore, an unbalanced bridge that can directly convert into a voltage signal results in the resistance change under an applied pressure. For $\Delta R \ll R$, the relationship between the voltage and resistance can be expressed as follows:

$$\Delta V = \frac{r}{(1+r)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) V_{in} \quad (4)$$

where $r = R_2/R_1 = R_3/R_4$, ΔR_i is the ith resistance change, R_i is the ith zero-stress resistance, V_{in} is the bridge-input voltage, and ΔV is the differential output voltage.For $R = |R1| = |R2| = |R3| = |R4|$ in Eq. (4) with the neglection of dimensional change, the mechanical stress, the total resistance change (ΔR) and the output voltage relation can be expressed as follows:

$$\left|\frac{\Delta V}{V}\right| = \left|\frac{\Delta R}{R}\right| = \left|\frac{\Delta \rho}{\rho}\right| = \sigma_l\pi_l + \sigma_t\pi_t \quad (5)$$

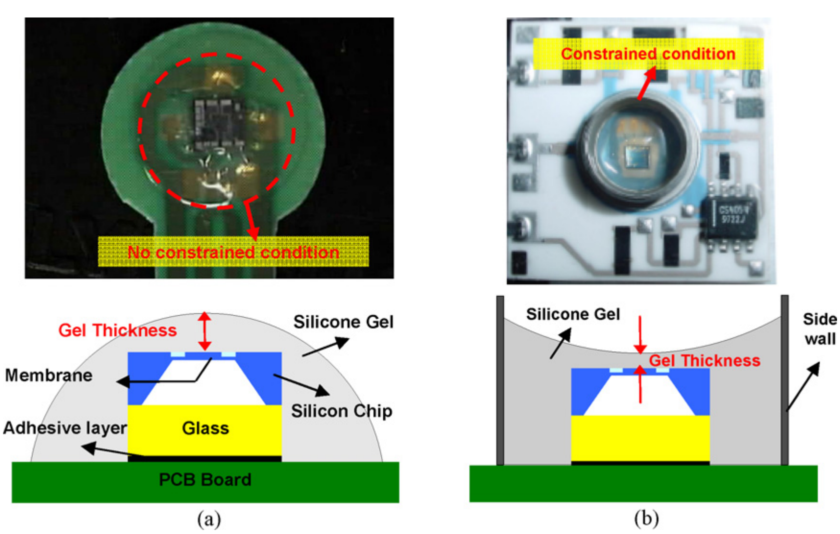

Fig. 1. The two types of silicone gel to protect the die surface and the cross section of packaged pressure sensor (not to scale): (a) model1; (b) model2 [13].

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