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A high sensitivity and high linearity pressure sensor based on a peninsula-structured diaphragm for low-pressure ranges

Xian Huang[a,b], Dacheng Zhang[b,*]

[a] Shenzhen Graduate School, Peking University, Shenzhen, PR China
[b] Institute of Microelectronics, Peking University, Beijing, PR China

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ABSTRACT

The trade-off between sensitivity and linearity has been the major problem in designing the piezoresistive pressure sensors for low pressure ranges. To resolve the problem, a novel peninsula-structured diaphragm with specially designed piezoresistors was proposed. Finite element method (FEM) was adopted for analyzing the sensor performance as well as comparisons with other sensor structures. In comparison to flat diaphragm, the proposed sensor design could achieve a sensitivity increase by 11.4%, nonlinearity reduction of 60% and resonance frequency increase of 41.8%. In addition, the modified peninsula-structured diaphragms featuring a center boss have been optimized to achieve ultra-low nonlinearities of 0.018%FFS and 0.07%FFS for the 5 kPa and 3 kPa pressure ranges respectively with higher sensitivities as compared to the CBM (cross beam membrane) and hollow stiffening structures. In accordance with the FEM results, the fabricated pressure sensor with the peninsula-structured diaphragm showed a sensitivity of 18.4 mV/V full-scale output and a nonlinearity error of 0.36%FSS in the pressure range 0–5 kPa. The proposed sensor structure is potentially a better choice for designing low pressure sensors.

1. Introduction

Attributed to the simple and low-cost fabrication process, MEMS (micro-electro-mechanical systems) piezoresistive pressure sensors have been in mass production for over three decades. Normally, the sensor is fabricated by bulk silicon micro-machining processing technique. The key component of the sensor is a thin square diaphragm which deflects when pressure is applied. Four Piezoresistors configured in a Wheatstone bridge are placed near the center of the diaphragm edge. The bridge converts the stress in the deflected diaphragm to an electrical signal. By adjusting the dimensions of the diaphragm, a wide measurement range of pressure can be obtained. Piezoresistive pressure sensors have been used in a wide range of applications, for instance, the automobiles [1] and process control [2]. Recently, there is a rapid growth in demand for the ultra-low pressure measurement in fields like biomedical (invasive measurements) [3], smart homes such as HVAC (heating, ventilation and air conditioning) controls [4] and aerodynamics such as wall/wing pressure measurement [5,6]. In order to apply for ultra-low pressure (for example $\leq$5 kPa) measurement, the sensitivity should be significantly improved to maintain an appropriate sensor output (for example $\geq$15 mV/(V FFS)) for signal processing. Based on the mechanical behavior of the flat square diaphragm, sensitivity is proportional to the square of the ratio of diaphragm width to diaphragm thickness. Thus, sensitivity can be increased by a larger width/thickness ratio. Unfortunately, the nonlinearity error increases with this ratio at a much faster rate [3], a non-tolerable nonlinearity error (for example >1.0%FFS) may be occurred during the sensitivity optimization process. Therefore, the nonlinearity problem involved in the low pressure sensors should be solved to open the new areas of applications.

Various types of modified diaphragms for the fabrication of low pressure sensors have already been reported to resolve the nonlinearity problem. In order to increase the stiffness of the diaphragm, center bosses were often added to the diaphragm [7,8]. It was an effective method to reduce the nonlinearity error. However, the reduction of nonlinearity error was achieved at the expense of sensitivity or sensor size. Besides, the additional center mass would increase the acceleration sensitivity of the diaphragm, which was detrimental for the stability of the sensor for high sensitivity and accuracy applications. To tackle this problem, Kinnell [9] introduced a novel hollow stiffening structure to replace the solid center boss and a 30 mbar (3 kPa) full-scale differential pressure sensor with the hollow stiffening structure was fabricated. The sensor had perfect performances with a sensitivity of 18 mV/V full-scale output and linearity <0.4%FSS. The sensor allowed the advantages gained by a stiffening boss in terms of sensor

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[*] Corresponding author. Tel.: +86 1062754431.
E-mail addresses: huangxian2010@pku.edu.cn, huangxian1988@163.com (X. Huang), dchzhang@ime.pku.edu.cn (D. Zhang).

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linearity without either the negative effects of acceleration sensitivity or unnecessary increase in die size. Based on the electrochemical etch-stop technology, the hollow stiffen structure also had the advantages of high precision diaphragm thickness/sensor performance control. Nevertheless, the fabrication process for the hollow stiffening structure was relatively complicated and the key processes (including electrochemical etch-stop and fusion bonding process) require specialized production facilities which have not been widely adopted in foundries yet. The front-side beam diaphragm first proposed by Bao [10] has also been widely adopted for low pressure sensor design. Recently, a novel front-side cross beam membrane (CBM) structure was proposed by Tian [11] and further developed by Yu [12] for micro pressure measurement. Tian's CBM structure exhibited perfect linearity and stability performance, but the sensitivity was relatively low (7.081 mV/kPa, DC power 4.57 V) for measuring 5 kPa pressure. Yu combined the CBM structure with a double-side center boss for measuring absolute micro pressure lower than 500 Pa. High sensitivity and high overload resistance were achieved, but the nonlinearity problem (3.046%FSS) remained unsolved.

Many factors that influence the nonlinearity performance of the low pressure sensors have also been reported. Matsuda [13] presented the nonlinear piezoresistance effects in silicon. Lin [14] studied the sensitivity and nonlinearity issue on the pressure sensors with a half Wheatstone bridge configuration by characterizing the diaphragm thickness and the length of sensing resistors. Chiou [15] discussed the linearity performance of the pressure sensor under high residual stress induced by passivation films and anodic bonding. However, in previous works that applied structured diaphragm for pressure sensor design, only limited discussion concerned the influence of pattern and positioning of piezoresistors on sensor's nonlinearity performance. Despite the growing achievements in low pressure sensor design and fabrication, additional research and considerable progress are still needed to further improve the performances of the pressure sensor such as the increasing of sensor output and stability, the decreasing of nonlinearity error, chip size and fabrication cost.

In our study, a novel high sensitivity and high linearity pressure sensor based a peninsula-structured diaphragm for low pressure ranges was proposed. The proposed sensor structure could have the advantages of low fabrication cost, high sensitivity, good linearity and diaphragm stability over other existing structures. In the following sections, stress distribution characteristics for the proposed diaphragm under pressure loading were studied in detail by FEM analysis. The influences of the pattern and positioning of piezoresistors as well as the lithography alignment errors on sensor's performance were discussed. Comparisons with other sensor structures with typical flat, center-bossed diaphragm and recently proposed CBM, hollow stiffen structure were carried out respectively in terms of sensitivity and linearity to demonstrate the superiority of the sensor structure. Moreover, modified peninsula-structured diaphragms featuring a center boss have been optimized to achieve ultra-low nonlinearity errors with higher sensitivities. A fabrication process for the proposed sensor with the peninsula diaphragm was presented in detail. Finally, the fabricated sensor devices were tested and compared with the FEM result, which verified the accuracy of the FEM simulation.

2. Background

2.1. Sensor output

Diaphragm type piezoresistive pressure sensors are usually arranged into a full Wheatstone bridge configuration with two piezoresistors (R_2 and R_3) loaded longitudinally and two (R_1 and R_4) loaded transversely. When the pressure is applied on the diaphragm, R_2 and R_3 will have the same positive increment ΔR_2, while R_1 and R_4 will have the same negative increment ΔR_1. Due to different patterning and positioning of the piezoresistors, the resistance increment $|\Delta R_1|$ normally differs to $|\Delta R_2|$. Based on the Wheatstone bridge circuit, the correlation between the output voltage and the resistance can be described as

$$V_{\text{out}} = V_{\text{in}} \frac{\Delta R_2 - \Delta R_1}{2R + \Delta R_2 + \Delta R_1} \qquad (1)$$

where V_{in} is the source DC power and V_{out} is the output voltage. R is the resistance of the piezoresistors. Since the resistance change is proportional to the mechanical stress, for low doped P-type piezoresistors along <1 1 0> direction: $(\Delta R/R) = \sigma_{lt} \times (\pi_{44}/2)$ (π_{44} represents the shear piezoresistance coefficients and σ_{lt} represents the average stress difference between longitudinal and transverse directions within the resistor) [16]. Then the correlation between the output voltage and the mechanical stress can be obtained as

$$V_{\text{out}} = V_{\text{in}} \frac{\sigma_{\text{lt}_2} - \sigma_{\text{lt}_1}}{(4/\pi_{44}) + \sigma_{\text{lt}_2} + \sigma_{\text{lt}_1}} \qquad (2)$$

where σ_{lt_2} and σ_{lt_1} are average stress for resistor R_2 and R_1 respectively.

2.2. Nonlinearity error

The terminal based nonlinearity error of the pressure sensor is defined as [15]

$$\text{NL} = \frac{\text{Delt}}{\text{FSS}} \times 100\% \qquad (3)$$

where Delt is the voltage output difference between the real voltage output and the ideal linear output. The full-scale span (FSS) is the voltage range of the full pressure range. NL is the terminal based nonlinearity error.

There are two major sources for the nonlinearity error of a diaphragm type piezoresistive pressure sensor with the Wheatstone bridge configuration [3]. The first source is the nonlinear dependence of the stress with the applied pressure when large deflection of the diaphragm occurs (balloon effect). The second source is the unbalanced stress ($\sigma_{\text{lt}_2} + \sigma_{\text{lt}_1}$ in Eq. (2)) among piezoresistors in the Wheatstone bridge. If a stress unbalance appears between R_1 and R_2, the stress term $\sigma_{\text{lt}_2} + \sigma_{\text{lt}_1}$ would have a non-zero value, the sensor output would not be proportional to the applied stress even if all the stress terms in Eq. (2) change linearly under small deflection.

For flat diaphragm, the trade-off between sensitivity and linearity will become irreconcilable when designing sensors for very low pressure measurement as discussed in the introduction. In our case, for the 5 kPa full range pressure sensor designed based on the flat diaphragm with a thickness of 10 μm, the output voltage could reach 100 mV (the source voltage is 5 V and the doping concentration of piezoresistors is 2.5e18 cm^{-3}) by adjusting the diaphragm's width. However, the nonlinearity error would exceed 1.2%FFS at the same time. In order to meet simultaneously the NL design criteria within 0.5% and the output beyond 100 mV for measuring the 5 kPa pressure, the flat diaphragm of the sensor must be modified.

3. Sensor design

A novel sensor structure featuring a peninsula-structured diaphragm was proposed to solve the abovementioned contradiction between the nonlinearity and sensitivity as shown in Fig. 1. The peninsula structures were located near the diaphragm edge with narrow beams connecting to the Si pedestal. Four piezoresistors on