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Design optimization and fabrication of a novel structural piezoresistive pressure sensor for micro-pressure measurement

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ABSTRACT

This paper presents a novel structural piezoresistive pressure sensor with a four-beams-bossed-membrane (FBBM) structure that consisted of four short beams and a central mass to measure micro-pressure. The proposed structure can alleviate the contradiction between sensitivity and linearity to realize the micro measurement with high accuracy. In this study, the design, fabrication and test of the sensor are involved. By utilizing the finite element analysis (FEA) to analyze the stress distribution of sensitive elements and subsequently deducing the relationships between structural dimensions and mechanical performance, the optimization process makes the sensor achieve a higher sensitivity and a lower pressure nonlinearity. Based on the deduced equations, a series of optimized FBBM structure dimensions are ultimately determined. The designed sensor is fabricated on a silicon wafer by using traditional MEMS bulk-micromachining and anodic bonding technology. Experimental results show that the sensor achieves the sensitivity of 4.65 mV/V/kPa and pressure nonlinearity of 0.25% FSS in the operating range of 0–5 kPa at room temperature, indicating that this novel structure sensor can be applied in measuring the absolute micro pressure lower than 5 kPa.

1. Introduction

The MEMS piezoresistive pressure sensors have been well developed and widely used in the industrial and commercial applications with the vigorous development of silicon micromachining technology [1,2]. Recently, with the market expansion of electronic devices including automobiles, aerospace and portable electronics, great research effects have been motivated again to develop high accuracy and micro-pressure measurement sensors which feature high reliability, low costs and mass fabrication capability [3–5]. The key principle of the sensor is based on a thin membrane that deflects when a pressure is applied on the membrane surface. A Wheatstone bridge is built to transduce the resistance change to voltage by means of the piezoresistive effect [6].

During the past years, several typical membrane structures of piezoresistive pressure sensors have been developed. As it is known, the structure of the membrane plays an important role in the performance of the sensor. C-type membrane, which formed by a cavity on the silicon wafer like the alphabet "C" from the side face, was the first proposed structure and was widely used for measuring the pressure of gas or water [7,8]. However, a thin C-type membrane utilized in the low pressure measurement usually results in a dramatic drop in the mechanical nonlinearity error. Severe pressure nonlinearity (*PNL*) may cause a high-sensitivity device of little practical value once it is beyond a certain range [9]. To solve this problem, the E-type membrane structure featured a central island mass was introduced, but this structure sacrificed the sensitivity of the sensor because of the stiffening of the membrane [10]. Sensitivity is proportional to the (membrane length)/(membrane thickness) ratio (L/H), so it can be increased by a larger ratio of that quantity. Unfortunately, the pressure nonlinearity increases with this ratio at a much faster rate, as the pressure nonlinearity of the pressure-to-stress conversion is proportional to $(L/H)^4$ [11]. Thus, the contradiction between sensitivity and linearity is always irreconcilable for traditional membrane structure. In order to improve the accuracy of the sensor, namely, obtain high sensitivity and low pressure nonlinearity synchronously, previous efforts were mainly focused on the following three aspects.

For the first aspect, design a novel structure and create stress concentration regions (SCRs) on the surface of the membrane. All the piezoresistors can be placed on the SCRs and the piezoresistive sensitivity can be improved with a small deflection of the membrane. For example, Yu et al. [12] developed a beams-membrane-mono-island (BMMI) structure to create SCRs and localize more strain energy within a relatively narrow space. The sensor achieved a high sensitivity of 11.098 μV/V/Pa in the operating range of 500 Pa at room temperature,

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although its pressure nonlinearity of 3.046% FSS was a little high. Tian et al. [13] designed a novel micro-pressure sensor with a cross-beam membrane (CBM) structure to enhance stress concentration on the sensitive beams. The sensor obtained a fine sensitivity of 7 mV/kPa and a low pressure nonlinearity of 0.19% FSS within the range of 0–10 kPa, which achieved a high accuracy of the sensor due to the creation of SCRs.

For the second aspect, an alternative option is to stiffen the membrane of the sensor and, consequently, reduce its deflection. According to the definition of the pressure nonlinearity [14], a small membrane deflection will lead to a drop in the gradient of the output curve, thereby reducing the difference between the real output and ideal linear output is an effective way to improve linearity. Kinnella et al. [15] presented a membrane with a thin-walled hollow stiffening structure to lessen the 'balloon effect' [16], getting a pressure nonlinearity of less than 0.40% FSS. H. Sandmaier et al. [17] proposed a sensor chip structure based on a narrow mass in the center of the membrane to make the membrane become harder and decrease its deflection. A lower pressure nonlinearity of 0.05% FSS was obtained, but the sensitivity was only 3.5 μV/V/Pa for the measurement of 10 kPa.

Finally, many new raw materials for the membrane were developed to improve the overall performance of the sensor. For instance, Pramanik et al. reported that nanocrystalline silicon was used as active piezoresistors for achieving high accuracy [18]. For high-precision applications, ceramic-based substrate has also been chosen to fabricate the sensor [19]. Some other novel materials, such as polysilicon [20], SiC [21], diamond [22] and silicon nanowires [23] were all adopted to fabricate sensor chips. Although the performance of those pressure sensors have been improved a lot because of these new materials, the performance still cannot satisfy the requirement of achieving high sensitivity and low pressure nonlinearity at the same time. Besides, there are still many practical difficulties in bulk production because of the technical problems.

In consideration of all the advantages and disadvantages for above models, it is found that creating SCRs are beneficial to utilize the strain energy for the piezoresistors, then the sensitivity can be improved definitely. Also, stiffening the membrane can avoid a large deformation, and then the pressure nonlinearity is expected to control over a small range. The objective of this paper is to design a novel structural membrane combining the advantages of these two types of models mentioned above. New materials are not considered for this paper, as some technical processes are not mature enough for us.

In this study, we reported a novel four-beams-bossed-membrane (FBBM) structural MEMS pressure sensor. By introducing beams into the membrane, the SCRs were expected to be formed. In addition, a central mass not only could play a role in stiffening the membrane, but also improved the performance of the high overload resistance due to the existence of the island to prevent an oversize displacement. This novel sensor was expected to alleviate the contradiction between the sensitivity and linearity and could be used in the measurement of micro pressure. The properties of the sensor, including the mechanical performance and the relative equations for accurate design and fabrication were fully studied. The fabricated sensor device was tested and compared with the FEA results, which proved the accuracy of the design process.

2. Sensor design

2.1. Design principle

For piezoresistive pressure sensors, a square membrane is always used in consideration of its high stress and easy processing when compared with circular and rectangular ones in the same size condition. According to the theory of elasticity, the maximum stresses of the square, rectangular and circular membranes are given by the following equations [24]:

$$\sigma_{\mathrm{sm}} = 0.308P\left(\frac{L}{H}\right)^2(1-\mu^2) \tag{1}$$

$$\sigma_{\mathrm{rm}} = 0.383P\left(\frac{B}{H}\right)^2(1-\mu^2) \tag{2}$$

$$\sigma_{\mathrm{cm}} = 0.75P\left(\frac{R}{H}\right)^2(1-\mu^2) \tag{3}$$

where σ_{sm}, σ_{rm} and σ_{cm} are the maximum stresses for the square, rectangular and circular membranes, respectively. P is the applied pressure; H is the membrane thickness; μ is the Poisson ratio; and L is the side length of the square membrane, B is the width of the rectangular membrane, and R is the radius of the circular membrane. By assuming that membrane thickness H and applied load P are totally same for the three models, additionally, L is 1.2 times B and 2 times R respectively, the following relationships can be obtained:

$$\sigma_{\mathrm{sm}} \approx 1.16\sigma_{\mathrm{rm}} \approx 1.64\sigma_{\mathrm{cm}} \tag{4}$$

which means an ~15% and ~60% improvement for the stress can be achieved by choosing the square membrane rather than other two types.

According to the small deflection theory, only when the deflection is smaller than 1/5 thickness of the membrane, this theory works, and then the pressure nonlinearity below 1.0% FSS is possible to obtain and the strain-displacement relations are linear [25]. Therefore, keeping the deflection less than 1/5 thickness of the membrane has a positive effect on the linearity of the sensor, and normally, it is possible to obtain high sensitivity and low pressure nonlinearity simultaneously.

The piezoresistive effect has been widely used as the mechanism of the pressure sensor. The resistance of a doped resistor will be changed when the membrane surface experiences a strain or deformation [26]. For the P-type silicon wafer, the largest piezoresistive coefficient is emerged along the crystal direction [1 1 0]. Therefore, in the design, all of the resistors should be aligned along the crystal direction [1 1 0] [27]. In this case, the relationship between resistance variation and stress can be expressed by Eq. (5) [28]:

$$\begin{aligned}\frac{\Delta R}{R} &= \frac{1}{2}(\pi_{11}+\pi_{12}+\pi_{44})\sigma_l + \frac{1}{2}(\pi_{11}+\pi_{12}-\pi_{44})\sigma_t \\ &= \frac{1}{2}(\pi_{11}+\pi_{12})(\sigma_l+\sigma_t) + \frac{1}{2}\pi_{44}(\sigma_l-\sigma_t)\end{aligned} \tag{5}$$

where σ_l and σ_t are the longitudinal stress and the transverse stress respectively. π_{11}, π_{12}, and π_{44} are the piezoresistive coefficients whose values under low doping concentration at room temperature are listed in Table 1. For P-type silicon, π_{44} is far larger than π_{11} and π_{12}, so the effect of π_{11} and π_{12} can be neglected in the calculation. To achieve a high sensitivity, piezoresistors should be located at the place where the stress difference between σ_l and σ_t reaches the maximum.

The mechanical stress calculated by simulation should be converted into voltage in such a way that the stress value can be used to predict the equivalent output electrical signal [29]. In this case, the relationship between output voltage and stress can be obtained by Eq. (6) [30]:

$$\frac{U_{out}}{U_{in}} = \frac{\pi_l\left(\sum_{i=1}^{n}\sigma_{li}\nu_i\right) + \pi_t\left(\sum_{i=1}^{n}\sigma_{ti}\nu_i\right)}{\sum_{i=1}^{n}\nu_i} \tag{6}$$

where U_{out} is the output voltage, U_{in} is the input voltage, i is the

Table 1
Piezoresistive coefficients under low doping concentration at room temperature [24].

Material	ρ (Ω·cm)	$\pi_{11}10^{-11}$ (Pa^{-1})	$\pi_{12}10^{-11}$ (Pa^{-1})	$\pi_{44}10^{-11}$ (Pa^{-1})
P-type silicon	7.8	+6.6	−1.1	+138.1
N-type silicon	11.7	−102.2	+53.4	−13.6