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DESIGN AND SIMULATION OF A NOVEL PIEZORESISTIVE PRESSURE SENSOR FOR GUIDEWIRES

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Abstract

This paper proposes a new design of a piezoresistive pressure sensor used for guidewires which can detect in the range of 0 – 200 mmHg pressure. The sensor is mainly designed based on the maximum sensitivity through theory and finite-element analysis (FEM). We conducted optimization of the shape and structure of the sensor. Rectangular membrane is chosen due to the constraint of width dimension of guidewires and the added sensitivity than the traditional square one. Also, the shaped membrane design was proven to be advantageous in terms of high sensitivity (0.314mV/V/kPa) in low pressure biomedical applications compared to the flat diaphragm design of commercial sensors used for cardiovascular measurements.

1. Introduction

Regarding to WHO (World Health Organization), cardiovascular diseases (CVDs) are the number one cause of death globally. An estimated 17.9 million people died from CVDs in 2016, representing 31% of all global deaths [1]. Of these deaths, 85% are due to heart attacks and strokes, which are mainly caused by blockage in the heart's blood supply due to the fatty deposits in the artery's walls, known as atherosclerosis. To assess the blockage amount of the stenosis, a process called Fractional Flow Reverse (FFR) was nominated, a guidewire-based procedure that can accurately measure blood pressure and calculate blockage level using the pressure ratio: distal coronary pressure (Pd) to the lesion over aortic pressure (Pa) to the lesion (*Figure 1*). Pressure sensor plays a vital role in this measurement with the aim of achieving better range, resolution and sampling rate with as small as possible size.

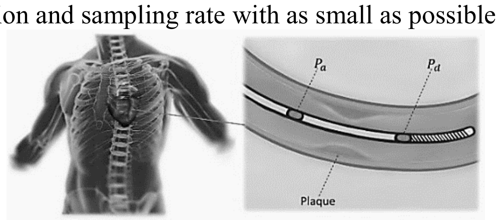

Fig. 1 2 Piezoresistive pressure sensors in the guide-wire measuring Pd and Pa on both side of the stenosis in the coronary artery.

2. Structure design and analysis

In this work, we propose a new MEMS piezoresistive pressure sensor design in the aim of achieving better sensitivity and lower non-linearity. Although many diaphragm structures have been proposed, linearity and sensitivity balancing problem remains crucial in pressure sensor design.

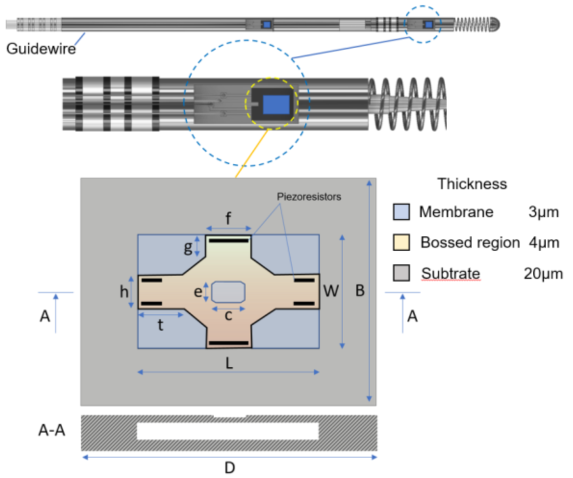

Fig. 2 Design of proposed sensor with location of 4 piezoresistors

Conventional MEMS piezoresistive pressure sensors possess low sensitivity and suffer from thermal drift, which causes a problem in precise biomedical applications. To overcome this problem, diaphragms must be thinner. However, this exposes a tradeoff between sensitivity and nonlinearity due to balloon effect, also error due to non-uniformity of micromachined diaphragm. Due to limitation of the width size (guidewire diameter should be lower than minimum coronary artery diameter 800µm[2]), we introduce the rectangular shape membrane which can be extend in length and be more sensitive than the traditional square one. The desire is to increase the maximum stress at the edge of the membrane, have uniform stress where four resistors are located on beams to form a full-balanced Wheatstone bridge. There is bossed region which is thicker than the membrane region in order to enhance the maximum stress and also the connecting part between the 4 peninsulas in order to stiffen the membrane on top surface. We did not consider fabricating boss structure on the rear side as mentioned in [3], [4] due to fabrication limitation. The relation between membrane size, thickness and applied pressure are described in the equation [5]:

$$\sigma_x = 0.294 \times \frac{L \times W}{H^2} \times P \qquad (1)$$

where σ_x, L, W, H, P are conducted maximum stress, membrane length and width, membrane thickness, applied pressure, respectively. Cavity SOI wafer is chosen as the substrate because of its good characteristics (high and predictable Young's modulus, high yield strength, guarantee thermo stability).

3. Optimization

Considering the above equation, we did several parametric simulation studies to optimize membrane length and width, crossbeam width, peninsula shapes and location (*Figure 2*). The dimensions are described below (*Table 1*):

Table 1. Parametric sizes (μm) of the proposed sensor

D	B	L	W	f	g	t	h	c	e
240	180	160	100	36	20	40	26	30	20

The structure gives an advantage in concentrating the stress on the four edged-beam. Outside mass also enhance the stress on the beams, stiffen the membrane and avoid oversize deformation. The stand-out point of this structure compared to other designs is the center "valley" which deflect as good as a flat membrane design and the connecting part between those outbound-mass help stiffening the membrane.

Using simulation program Comsol^{TM}, we confirmed the maximum stress located on the membrane. A pressure level of 200mmHg(26.667kPa) was applied on the top surface region (*Figure 3*). The material is silicon, properties used in the simulations were as follows: Young's modulus of 160GPa, density $\rho = 2329\ kg/m^3$ and Poisson's ratio of 0.22.

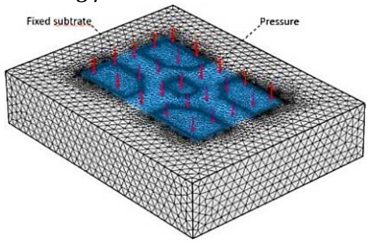

Fig. 3 Meshed model of the proposed sensor

We used π_{44} as the piezoresistive coefficient of each resistor. The value is for p-type silicon (100) plane, $\pi_{44} = 138.1 \times 10^{-11} Pa^{-1}$ [6]. The average longitudinal stress on R_1 and R_3 is σ_{x1}; average transvere stress is σ_{y1}; $\sigma_{lt1} = \sigma_{x1} - \sigma_{y1}$. The average longitudinal stress on R_2 and R_4 is σ_{y2}; average transvere stress is σ_{x2}; $\sigma_{lt2} = \sigma_{x2} - \sigma_{y2}$. Based on the Wheastone bridge circuit, the equations of the output voltage[5], sensitivity[6] and nonlinearity error[7] can be expressed as follows:

$$V_{out} = V_{in} \frac{\sigma_{lt1} - \sigma_{lt2}}{\left(4/\pi_{44}\right) + \sigma_{lt1} + \sigma_{lt2}} \qquad (2)$$

$$S = V_{out}/(\mathrm{P}) \qquad (3)$$

where P *is* operating pressures, respectively; V_{out} is full-scale output.

$$NL_i = 100\% \times \frac{\left[V_{out(p_i)} - \frac{V_{out(p_{max})}}{p_{max}}(p_i)\right]}{V_{out(p_{max})}} \qquad (4)$$

where NL_i and p_i are the nonlinearity error and the pressure at the calibration points. The max error value is called the nonlinearity of the sensor. The FEM result depicts that the maximum stress 13.6(MPa) at the edge of the membrane(*Figure 4*). The value is far less than tensile ultimate stress of silicon 7000 MPa so the sensor would not be cracked under 200mmHg pressure.

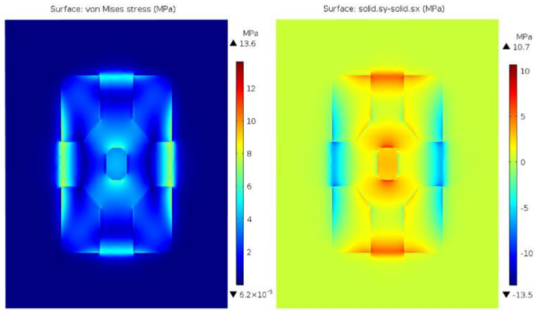

Fig. 4 Meshed model of the proposed sensor

We consider the design 100x160x3μm because of high sensitivity and lowest nonlinearity error (-0.01%) (*Figure 5*).

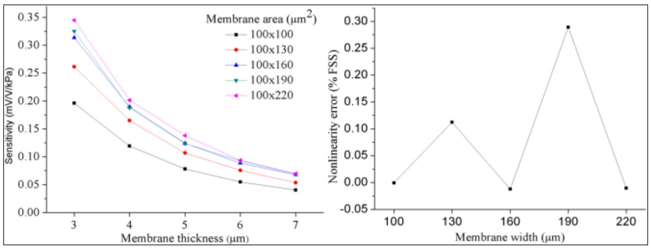

Fig. 5 Sensitivity (FSO) and Nonlinearity error (%FSS)

Futhermore, we did some comparision between miniaturized designs with the proposed one (*Table 2*).

Table 2. Sensitivity(mV/V/kPa) of different designs

Design	Flat[7],[8]	CM[9]	CBM[10]	CBCI[11]	**Proposed**
Sensitivity	0.301	0.255	0.292	0.284	**0.314**

Each design features introduce an added complexity to the fabrication and cost, but increases the sensitivity of the sensor.

4. Conclusions

Proposed design is potential with high sensitivity and low nonlinearity error. Future works consist of further optimization, fabricating a real sensor and measurements. We finally intend to apply this sensor design for guidewire applications.

Acknowledgements

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