Modeling an Optical Diaphragm for Human Pulse Pressure Detection

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Abstract: - This paper presents the modeling of an optical diaphragm behavior for human pulse pressure detection. In this study, the comparison between the performance of the polyimide and silicon nitride diaphragm has be analyzed. The effect of diaphragm's radius and thickness on static and frequency response are also investigated. The findings show that the polyimide diaphragm is more sensitive than the silicon nitride diaphragm. The radius of the polyimide diaphragm has more effect on the deflection, sensitivity and resonance frequency as compared to the diaphragm's thickness. It can be concluded that the polyimide diaphragm achieves the optimum performance in term of the deflection, sensitivity, and resonant frequency for human pulse pressure detection.

Key-Words: - Optical MEMS, Deflection, Resonance Frequency, Pressure Sensitivity, Pulse Pressure, Silicon nitride, Polyimide, Biosensor

1 Introduction

The shape of the arterial pressure waveform provides a measure of the arterial stiffness [1]. The pulse pressure waveform can be used to diagnose arterial stiffness. Arterial stiffness is buildup of fatty deposits (plaque) on the inside arteries walls. Plaques will reduce the blood's flow through the artery [2]. Commercial available miniature sensors regardless of their invasiveness can present only the percentage of arterial occlusions. There is no information about the degrees of sclerosis and stiffness of the arteries can be directly achieved by them. [3,4].

Most invasive pressure measurements utilize a fluid filled catheter that transfers measured pressure to an external transducer. While in noninvasive designs, sensing principles such as capacitive and piezoresistive have shown good potential in biomedical applications. However, a major problem associated with the piezoresistive pressure sensor is its inherent sensitivity to temperature [5-7].

In contrast to the piezoresistive pressure sensors, it is well known that the capacitive detection principle has high sensitivity. However, electrical connections to the sensor are very sensitive to noise. This happened due to small electrical capacitance. Therefore, electrical connections have to be made as short as possible. It will make the sensor packaging a big challenge [5].

Recent advances in optical Micro-electro-mechanical- system (MEMS) sensors have enabled the development of miniature sensors. The ability to guide signals to and from a measurement site has made the optical MEMS technology attractive in designing the pulse pressure sensor. In addition, the optical MEMS offer high adaptability in harsh environment and immunity to electromagnetic interference [8, 9].

This paper presents the modeling of an optical micro-diaphragm for human pulse pressure detection. The effect of polyimide and silicon nitride diaphragms on static and frequency response is analyzed.

2 Theory of a Circular diaphragm

The theory of circular diaphragm on deflection, sensitivity and resonance frequency of the diaphragm are presented.

2.1 Diaphragm deflection under applied pressure

The load-deflection method is used for elastic properties measurement of thin films [5, 10-12]. In this technique, the deflection of a fixed edge diaphragm is measured as a function of applied pressure. A circular diaphragm will be clamped rigidly at its edges as shown in Figure 1.

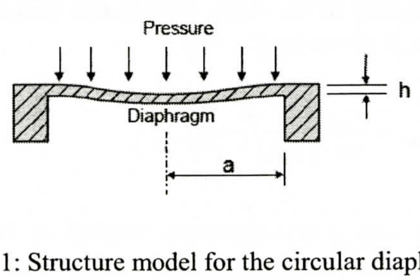

Figure 1: Structure model for the circular diaphragm

The diaphragm will be deflected under a

uniform applied pressure. The out-of-plane deflection of the diaphragm, y is a function of the pressure difference and the radial distance [10-12]:

$$y = \frac{3(1-\mu^2)P}{16Eh^3}(a^2 - r^2)^2 \quad (1)$$

where y is deflection, P is applied pressure, μ is Poisson's ratio, E is Young's Modulus, h is diaphragm's thickness, a and r are effective diaphragm's radius and radial distance respectively.

The maximum deflection, of the diaphragm as a function of applied pressure can be written as [11]:

$$y_c = \frac{3(1-\mu^2)a^4}{16Eh^3}P \quad (2)$$

2.2 Pressure Sensitivity

When the optical fiber is positioned facing the center of the diaphragm, the maximum deflection and pressure sensitivity will be analyzed. The pressure sensitivity (Y) is defined as the ratio between the deflection and the pressure difference [5, 11]. The sensitivity is normally used in evaluating the performance of the diaphragm as a pressure sensitive element.

As for silicon nitrite and polyimide diaphragms, their pressure sensitivity at the center of the diaphragm is given by equations (3) and (4) respectively [11]:

$$Y_c(siliconnit\,ride) = 8.585\times 10^{-11}\frac{a^4}{h^3}(\mu m/mmHg) \quad (3)$$

$$Y_c(polyimide) = 2.194\times 10^{-11}\frac{a^4}{h^3}(\mu m/mmHg) \quad (4)$$

where diaphragm's radius *(a)* and thickness *(h)* are in microns.

2.3 Resonance Frequency

Frequency response is another important issue in modeling of the micro-diaphragm. In this study, the diaphragm is defined as a free vibrating circular plate clamped rigidly at the edge. Resonance frequency of the diaphragm is given by [5, 11]:

$$f_{mn} = \frac{\alpha_{mn}}{4\pi}\sqrt{\frac{E}{3\rho(1-\mu^2)}}\left(\frac{h}{r^2}\right) \quad (5)$$

where α_{mn} and ρ are constants related to the vibrating modes of the diaphragm and mass density of the diaphragm's material, respectively.

3 Principle of operation

The optical sensor is demodulated by detecting the shift of the reflected or transmitted spectrum from the light source. By using light emitting diode (LED) as a light source, it will be transmitted via optical fibers. Figure 2 shows the proposed design of the optical sensor. The optical sensor consists of an optical fiber and the micro-diaphragm structure as pressure transducer.

Pulse pressure that is sensed from the surface of radial artery, will cause deformation of the diaphragm. Thus it will change the reflected or transmitted spectrum. The diffused components of the reflected light will strike the diaphragm which is in contact with the skin on the radial artery.

From the reflected spectrum, the cavity length of the sensor, deflection and corresponding pressure can be measured. The reflected waveform will produce the information about the arterial stiffness and elasticity of the artery [1].

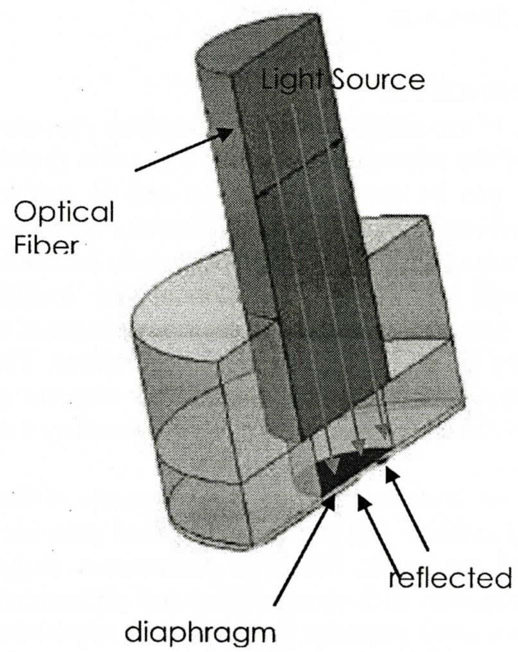

Figure 2: Proposed design of the optical MEMS sensor [4].

This study focuses on the modeling an optical micro-diaphragm for the human pulse pressure detection. The modeling and analysis of the diaphragm are presented in the next subsection. The analysis includes the static and frequency response of the diaphragm. The diaphragm material is chosen based on this analysis.

4 Design Specification

The optical sensor is targeted to sense the pulse pressure on the surface of human's radial artery. According to

[13-15], the diameter of normal human artery is between 2.5 to 3mm. Therefore, the overall sensor system must be smaller than the size of radial artery.

Since the sensor is externally attached to the human wrist, the pulse pressure will not create the same pressure as the blood exerts on the arteries wall [13]. The pressure will not be sufficient enough to displace the diaphragm by more than 1μm [13]. Therefore, miniature size diaphragm with maximum deflection of 1μm is needed.

In order to ensure the diaphragm operates in a linear range, the resonance frequency of the diaphragm should be at least 2.5 times larger than the applied frequency [9]. For pulse pressure detection, the diaphragm should be able to operate in the frequency range from 0 to 50 kHz. The overall diaphragm specification is presented in Table 1

Table 1: Diaphragm Specification

Parameter	Value
Pressure range	0-300mmHg
Frequency range	0-50kHz
Maximum Deflection	$\leq 1\mu m$

To successfully perform pulse pressure measurement, the sensor should have the following attributes: (i) miniature in size, (ii) adequate detection system to measure small diaphragm deformation, (iii) biocompatibility and (iv) appropriate dynamic range and sensitivity for small pulse pressure measurement.

5 Methodology

In this research, the circular diaphragm is clamped at the edge and modeled by using MEMS Software, (Intellisuite). The solid circular diaphragm has been designed in "Intellifab" module. Further analysis on the behavior of the diaphragm has been analyzed using "Thermoelectromechanical" module.

Two diaphragm materials are used to compare the performance of the diaphragm. The materials used are polyimide and silicon nitride. The comparison of material properties between silicon nitride and polyimide is shown in Table 2. The diaphragm is loaded with pressure ranging from 0 to 300mmHg [2].

The diaphragm's radius and diaphragm's thickness are also varied to study their effects on diaphragm behavior. The best model will be selected.

Table 2: Material Properties of Silicon Nitride and Polyimide

Material Properties	Silicon Nitride	Polyimide
Young's Modulus (GPa)	270	7.5
Poisson Ratio	0.27	0.35
Thermal Conductivity (W/cm/C)	0.032	8.06×10^{-6}
Specific Heat (J/gC)	0.71	4.21
Electrical Resistivity (Ωcm)	0.6	1×10^{-16}
Dielectric Constant	7.5	3.4
Density (g/cm^3)	3.44	1.33
Coefficient of Thermal Expansion (/°C)	2810×10^{-7}	810×10^{-7}

6 Results & Discussions

The simulation results are shown in Figure 3 and 4. Figure 3(a) illustrates the deflection in relation with diaphragm's radius and diaphragm's thickness. The 3-dimension graphs of sensitivity and resonance frequency are illustrated in Figures 3(b) and (c) respectively.

At a particular diaphragm's thickness, the deflection and sensitivity increase as diaphragm's radius increases (Figures 3(a) and (b)). The result also indicates that the thinner the diaphragm's thickness, the higher the deflection. This is phenomena is supported by Equations (1) and (2).

Figure 3(c) illustrates that the resonance frequency increased as the diaphragm's radius and diaphragm's thickness are small and thick respectively as supported by equation (5). The results indicate that the diaphragm's radius has more effect on deflection, sensitivity and resonance frequency as shown in Figure 3 (a)-(c).

The deflection curve for polyimide and silicon nitride diaphragms under applied pressure are shown in Figure 4(a). The maximum deflections of polyimide and silicon nitride are 0.9μm and 0.02μm respectively (Figure 4(a)). Based on the findings shown in Figures 4 (a) and (b), it can be concluded that the polyimide diaphragm achieves higher deflection and more sensitive than silicon nitride diaphragm.

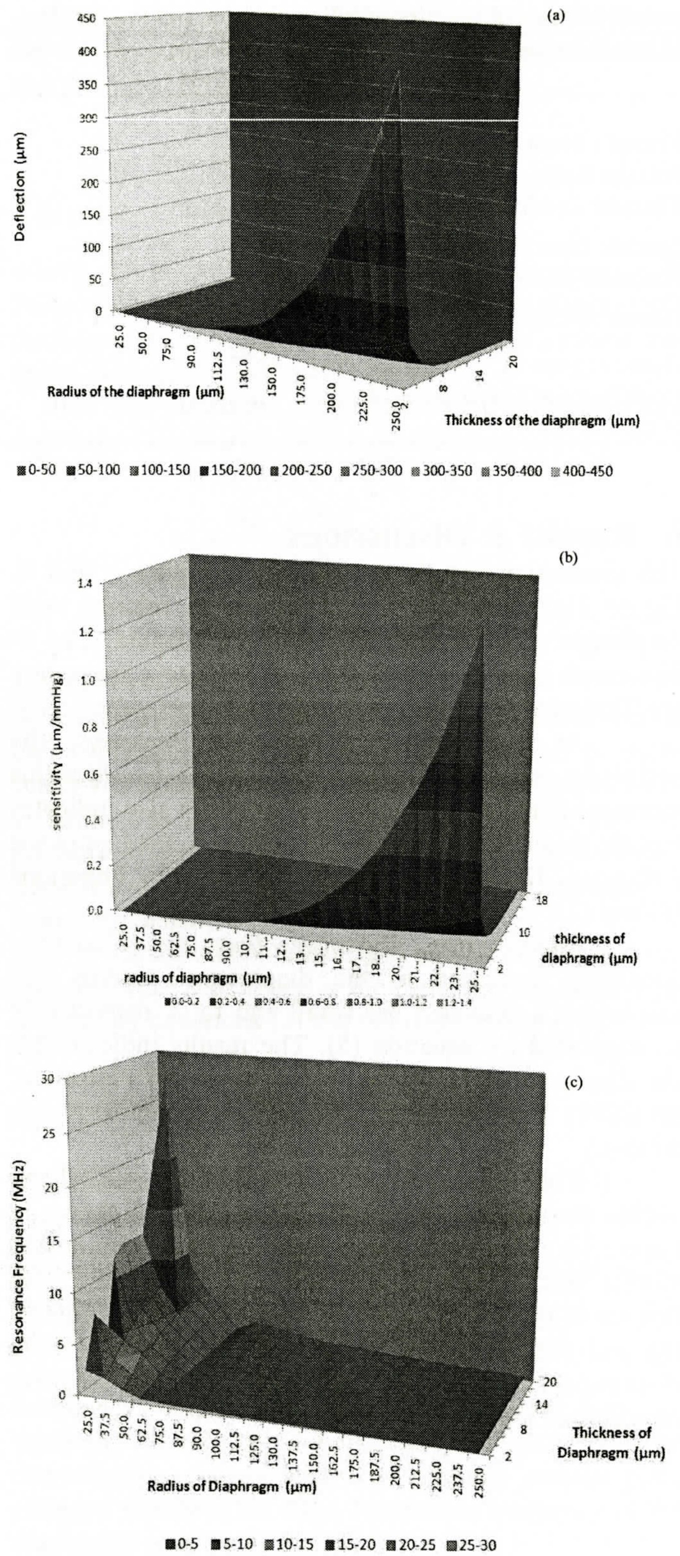

Figure3: The relationship among diaphragm's radius, diaphragm's thickness and: (a) Deflection (b) Sensitivity (c) Resonance Frequency

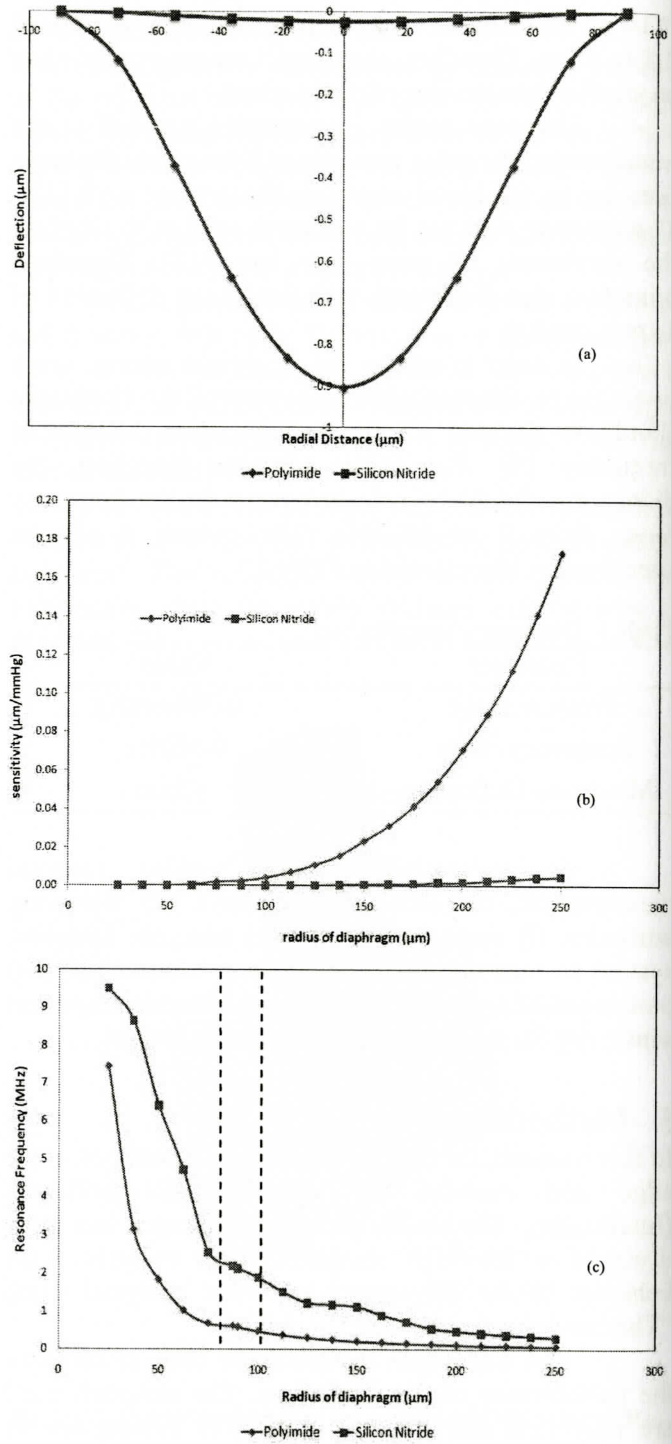

Figure 4: Analysis of diaphragm behavior: (a) Deflection curve under applied pressure. (b) Comparison of sensitivity between polyimide and silicon nitride diaphragm (c) Comparison of resonance frequency between polyimide and silicon nitride diaphragm

In Figure 4(b), the sensitivity increases as the diaphragm's radius is increased. This is supported by the other researcher findings in [5, 10, 12, 15-16]. The silicon nitride diaphragm possessed higher Young's Modulus and stiffer than the polyimide diaphragm (Table 2). Thus, the silicon nitride diaphragm is less sensitive than the polyimide diaphragm.

The comparison of resonance frequency between silicon nitride and polyimide diaphragm is shown in Figure 4(c). It can be concluded that the resonance frequency of polyimide diaphragm is lower than silicon nitride diaphragm. Although the given resonance frequency is low, the polyimide diaphragm has higher deflection and more sensitive than silicon nitride diaphragm.

Figures 3 and 4 have shown that the polyimide diaphragm achieves optimum performance in sensing the human pulse pressure as compared to silicon nitride diaphragm. The maximum deflection and resonance frequency of polyimide diaphragm is 0.9μm and 0.58MHz respectively. The sensitivity for polyimide and is 0.003μm/mmHg.

7 Conclusion

Modeling of the optical micro-diaphragm for pulse pressure detection has been presented. The results showed that when the diaphragm's radius and diaphragm's thickness is large and thin respectively, the deflection and sensitivity is increased whilst the resonance frequency is decreased.

Diaphragm's behavior on deflection, sensitivity, and resonance frequency are supported by analytical equation in Section 2 and in agreeable with other researchers [5, 10, 12, 15-16].

Findings indicate that polyimide diaphragm provides higher sensitivity and lower resonance frequency than silicon nitride diaphragm. Polyimide diaphragm has obtained optimum performance in optical micro-diaphragm modeling. The maximum deflection and sensitivity of polyimide is 0.9 μm and 0.003μm/mmHg respectively. The resonance frequency of polyimide diaphragm is 2.5 times larger than the applied frequency. Therefore, the polyimide diaphragm operates in optimum frequency response and satisfied maximum allowable deflection.

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