Modeling of a Polyimide Diaphragm for an Optical Pulse Pressure Sensor

K. Hasikin[1], *Student Member IEEE*, N. Soin[2], *Member IEEE*, F. Ibrahim[1], *Member IEEE*
[1]Dept. of Biomedical Engineering, University of Malaya, Lembah Pantai, 50603 Kuala Lumpur.
[2]Dept. Electrical Engineering, University of Malaya, Lembah Pantai, 50603 Kuala Lumpur.

***Abstract*-This paper presents the modeling of a polyimide diaphragm for an optical pulse pressure sensor. Polyimide is a type of polymer materials that possessed low linear coefficient of thermal expansion and has good thermal stability. The polyimide diaphragm has been designed and its performance is analyzed in terms of diaphragm deflection, diaphragm pressure sensitivity and diaphragm resonance frequency. Two design parameters namely diaphragm radius and diaphragm thickness are varied to study the diaphragm performance. It can be concluded that the modeled micro-diaphragm with a diaphragm radius of 90µm and diaphragm thickness of 4µm respectively has satisfied the maximum allowable deflection and operated in optimum frequency response.**

I. INTRODUCTION

Diaphragm based sensors are widely used in biomedical applications [1-4]. This type of the sensor typically consists of a micro-diaphragm as a pressure transducer. For this type of the sensor, a diaphragm performance will determine a complete sensor system performance. The diaphragm can be designed by using Micro-electro-mechanical Systems (MEMS) technology.

In this study, a diaphragm-based optical pulse pressure sensor is designed. A suitable material needs to be chosen to ensure an optimum performance. However, selection of the most suitable material for the diaphragm is a crucial part in designing an optical pulse pressure sensor.

Since the diaphragm is designed as pressure sensitive element in the optical pulse pressure sensor, it must have highest sensitivity. Therefore the optical pulse pressure sensor must have an adequate detection system to measure small diaphragm deformation. A chosen diaphragm material must be sensitive for small pulse pressure measurements.

There are five main categories of MEMS materials for the diaphragm as shown in Figure 1. The structural material or substrate material must be able to survive the various process steps. Spacer materials are usually completely or partially etched away to release the microstructure.

It may also be used to make molds for structures and protect the substrate or structural material from certain etching steps. Surface materials are also important for achieving electrical isolation. Besides that, active materials are incorporated on structures to exploit their special physical transduction characteristics.

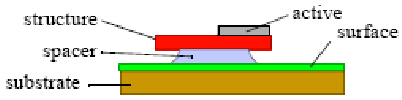


Figure 1: Categories of micromechanical materials

The diaphragm for the optical pulse pressure sensor can be implemented using different types of materials and manufacturing techniques. It includes silicon based, polymer based and metal based materials.

Silicon is the material used to create most integrated circuits used in consumer electronics in the modern world. Silicon has significant advantages engendered through its material properties. When it is flexed there is virtually no hysteresis and hence almost no energy dissipation [5].

Researches by [6-9] have shown that the silicon has a potential in invasive and noninvasive measurements. The silicon based materials such as silicon nitride, polysilicon and silicon dioxide are biocompatible and commonly used in biomedical applications.

Even though silicon is widely used in industry, crystalline silicon is still a complex and relatively expensive material to produce. However, polymer can be produced in huge volumes, with a great variety of material characteristics. MEMS diaphragm can be made from polymers by processes such as injection moulding, embossing and stereolithography [10]. Polymer diaphragm has been widely used for a limited detection space as presented in [11-18].

Synthetic polymeric materials have been widely used in medical disposable supplies, prosthetic materials, dental materials, implants, dressings and polymeric drug delivery systems. The main advantages of the polymeric biomaterials compared to metal and ceramic materials are ease of manufacturability to produce various shapes, reasonable cost, and availability with desired mechanical and physical properties [10].

Metals can also be used to create MEMS devices. Metals can exhibit very high degree of reliability. Besides that, metals are used as biomaterials due to their excellent electrical, thermal conductivity and mechanical properties [10].

However, the metal is rarely used as a sensing element for small range of pressure measurements. This is because metal possessed high stiffness and high Young's Modulus.

In this paper, the diaphragm for the optical pulse pressure sensor has been designed by using polyimide. The polyimide is one of the polymer materials that have been used in medical diagnostic applications [1-4]. Design parameters namely diaphragm radius and diaphragm thickness are varied to analyze the performance of polyimide diaphragm.

II. METHODOLOGY

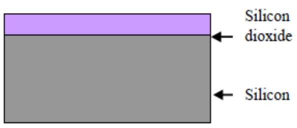
A. Diaphragm modeling

Designing a micro-diaphragm model is conducted by using MEMS Software, (*Intellisuite*). The designing of the diaphragm begins with fabrication process in *Intellifab* module.

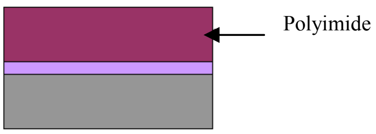
Fabrication process *in Intellifab* module consists of three layers of polyimide. It begins with deposition of silicon wafer as a substrate material and follows with deposition of silicon dioxide as an electrical isolation.

After the silicon wafer is cleaned, a 2µm release layer of silicon dioxide film is deposited on silicon wafer by plasma-enhanced chemical vapor deposition (PECVD) using tetraethoxysilane (TEOS). Then, a second layer of polyimide is deposited on the top of the release layer. The second layer with thickness of 30µm formed the cylindrical wall around the cavity of the sensor system.

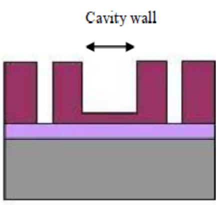
Diameter hole and cavity wall are patterned by using deep reactive ion etching. The diameter hole is smaller than the cavity wall which acts as an insertion stop for the optical fiber. To enhance reflection from the diaphragm, metal was evaporated onto the entire wafer. 200Å of chromium and 1000Å of titanium were coated on the wafer. After developing the diaphragm, micromanipulator was used to insert cleaved end of a single mode optical fiber. The simplified steps in diaphragm fabrication process are presented in Figure 2.



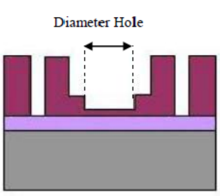
(a) Release layer of silicon dioxide is deposit onto the silicon wafer



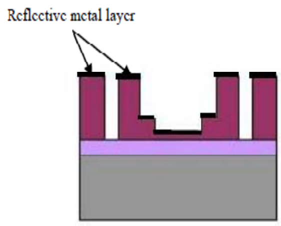
(b) Deposition of diaphragm material onto the silicon wafer



(c) Developing the cavity wall



(d) Diameter hole is formed by using DRIE



(e) Reflective metal layer is evaporated onto the whole wafer

Figure 2: Fabrication process for the diaphragm. (a) Release layer (2µm silicon dioxide) is deposit onto the silicon wafer. (b) Polyimide is deposit onto the wafer as diaphragm layer. (c) Diameter hole is pattern by using deep reactive ion etching (DRIE). (d) Etching process using DRIE to form cavity walls. (e) 200Å chromium and 1000Å Titanium will evaporate onto the whole wafer as a reflective metal layer.

B. Diaphragm Performance

When the diaphragm solid model is designed in *Intellifab* module, the diaphragm performance is analyzed by using *Thermoelectromechanical* module. Generally, there are three types of the diaphragm namely circular, square and rectangular diaphragms. Due to negligence of residual stress at the edge of diaphragm surface, the circular shape has been chosen as the diaphragm for the optical pulse pressure sensor [19].

In this stage, three design parameters namely diaphragm radius, and diaphragm thickness are varied to analyze the diaphragm performance. These design parameters are varied to study their effects on diaphragm deflection, diaphragm pressure sensitivity and diaphragm resonance frequency. The analysis of diaphragm performance is conducted by using finite element analysis (FEA) technique in *Thermoelectromechanical* module.

The FEA is a computational technique used to obtain approximate solutions of boundary condition problems in engineering [20]. Before fabricate the diaphragm, it is essential to do an analysis by using the FEA. This analysis is helpful because FEA gives close approximation to the actual prototype before it is fabricated.

Enormous amount of time and money can be saved by using the FEA. This is because, difficulties arise during designing the diaphragm can be detected and rectified at an early stage. Hence, trial and error approaches which are still encounter today can be avoided [20]. In addition, the FEA is a simulation technique that can analyze the behavior of the MEMS devices [21].

III. RESULT & DISCUSSIONS

Simulation results on diaphragm deflection are shown in Figures 3 and 4. The relationship between two design parameters and diaphragm deflection is illustrated in Figure 3.

Based on this figure, the diaphragm deflection is increases when the diaphragm is thick and diaphragm radius is large. It is depicted from the graph that the diaphragm radius has more effect on diaphragm deflection as compared to diaphragm radius (Figure 3).

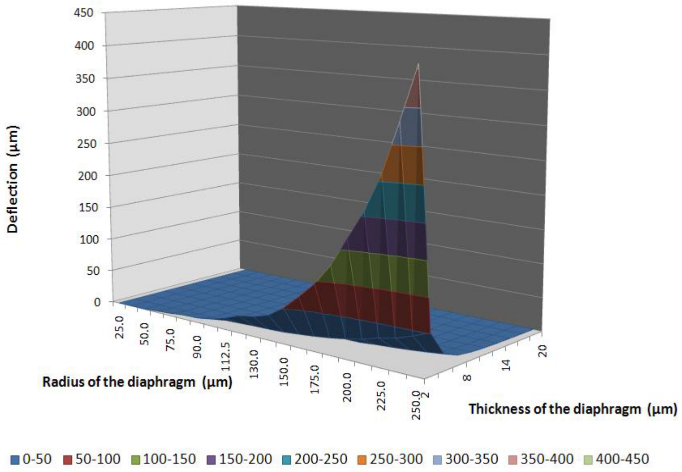


Figure 3: Relationship between design parameters and diaphragm deflection

These behaviors can also be supported by findings from other researchers [22-25] In addition, the relationship among the diaphragm deflection, diaphragm radius and diaphragm thickness can be supported by equation (1) as stated below:

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

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

Besides diaphragms radius and thickness, stiffness of the diaphragm is another important parameter need to be considered in diaphragm design. The stiffness of the diaphragm can be analyzed by studying a flexural rigidity of the diaphragm. The flexural rigidity is defined as a force couple required to bend a rigid structure [26] and can be presented in equation (2):

$$D = \frac{Eh^3}{12(1-\mu^2)} \qquad (2)$$

Relationship between diaphragm deflection and flexural rigidity is shown in Figure 4. It can be seen from the figure that when the diaphragm is thick, the flexural rigidity increases. Furthermore, the diaphragm deflection decreases with the increases of flexural rigidity. Equation (3) shows the correlation between diaphragm deflection and flexural rigidity [26].

$$y = \frac{P(a^2 - r^2)^2}{64D} \qquad (3)$$

The diaphragm is targeted to sense the pulse pressure on the surface of human's radial artery. According to [24,25,27], the diameter of normal human artery is between 2 to 3mm. Therefore, the complete sensor system must be smaller than the size of radial artery.

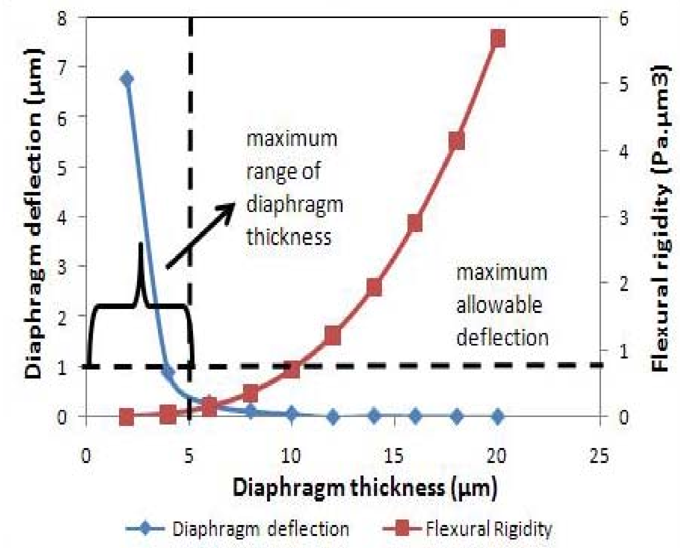


Figure 4: Diaphragm deflection and flexural rigidity with variation of diaphragm thickness

Since the sensor is externally attached to the human's wrist, the pulse pressure will not create the same pressure as the blood exerts on the arteries wall [27]. The pressure will not be sufficient enough to deflect the diaphragm by more than 1µm [27]. Therefore, miniature size diaphragm with maximum deflection of 1µm is needed.

The diaphragm deflection is closely related to diaphragm pressure sensitivity. The diaphragm pressure sensitivity is defined as a ratio of the changes in diaphragm deflection to pressure difference

The diaphragm pressure sensitivity is presented in equation (4):

$$S = \frac{\Delta y}{\Delta P} \qquad (4)$$

Thus by rearranging the equation (1) the diaphragms pressure sensitivity for polyimide diaphragm is given by:

$$Y_c(polyimide) = 2.194 \times 10^{-11} \frac{a^4}{h^3} (\mu m / mmHg) \qquad (5)$$

where a and h are in microns.

The diaphragm pressure sensitivity is important parameter since it determines how sensitive the diaphragm to deform with the change of applied pressure. Consequently, diaphragm with highest sensitivity is highly desirable in designing the diaphragm for the optical pulse pressure sensor.

Relationship of the diaphragm pressure sensitivity with variation of the diaphragm radius is shown in Figure 5. In this figure, it is shown that the diaphragm pressure sensitivity for polyimide diaphragm increases when the diaphragm radius is large as supported by equation (5).

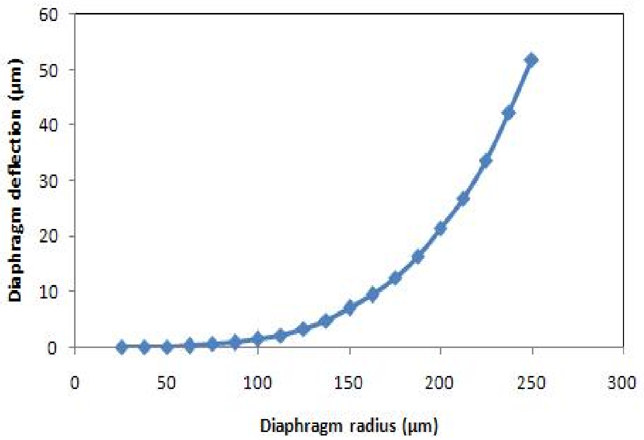


Figure 5: Diaphragm pressure sensitivity with variation of diaphragm radius

The relationship of diaphragm pressure sensitivity and flexural rigidity with diaphragm thickness is illustrated in Figure 6. The flexural rigidity increases when the diaphragm is thick and thus the diaphragm become less sensitive.

Therefore, it can be concluded that, diaphragm with low flexural rigidity is highly desirable. Therefore thin diaphragm must be chosen to ensure the diaphragm achieves highest deflection and sensitive to the applied pressure.

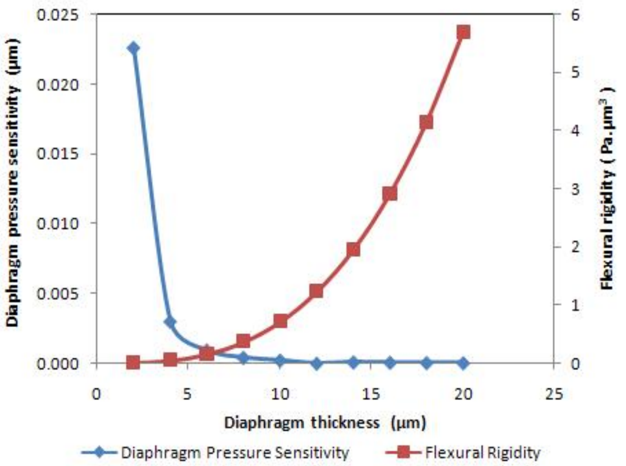


Figure 6: Relationship between diaphragm pressure sensitivity and flexural rigidity with the diaphragm thickness.

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 [28]. Diaphragm operates in linear range is highly desirable because the behavior of the diaphragm is easier to handle in calculation and measured [26, 29]. For pulse pressure detection, the diaphragm should be able to operate in the frequency range from 0 to 50 kHz.

As a result, diaphragm frequency response needs to be analyzed. This frequency response of the diaphragm is analyzed in terms of its resonance frequency. A resonance occurs when oscillation frequency matches a natural frequency of the diaphragm. Large amplitude of oscillation is induced at this resonance frequency.

The relationship between diaphragm deflection and resonance frequency with variation of diaphragm thickness is depicted in Figure 7.

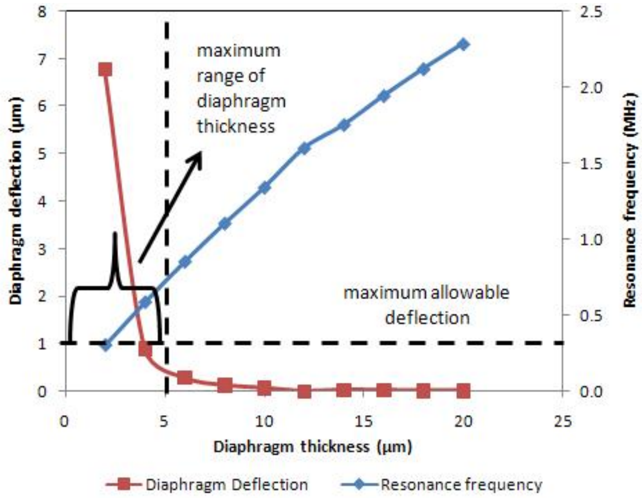


Figure 7: Diaphragm deflection and resonance frequency in relation with diaphragm thickness

As shown in this figure, the diaphragm achieves high deflection but low vibration frequency when the diaphragm is thick as supported by equation (6).

$$f_{mn} = \frac{\alpha_{mn}}{4\pi}\sqrt{\frac{E}{3\rho(1-\mu^2)}}\left(\frac{h}{r^2}\right) \quad (6)$$

where α_{mn} is a constant related to the vibrating modes of the diaphragm, h is thickness of the diaphragm, r is effective diaphragm radius, ρ is mass density of the diaphragm material, μ , and E is Poisson's ratio and Young's modulus of the diaphragm material respectively.

Therefore, in order to obtain maximum deflection of 1µm, diaphragm thickness should be selected in the range of 0 to 5µm.

According to diaphragm design specifications discussed before, the diaphragm should have a maximum deflection of 1µm. In addition, the diaphragm must operate in a frequency range of 0 to 50kHz. Due to these requirements, the diaphragm radius of 90µm and diaphragm thickness of 4µm was found to be the optimum design parameters for the diaphragm.

These diaphragm radius and diaphragm thickness give maximum diaphragm deflection and diaphragm pressure sensitivity of 0.9µm and 0.003µm/mmHg respectively. It is also shows that the diaphragm resonance frequency is 0.58MHz (2.5 times larger than applied frequency). Thus the chosen design parameters for the diaphragm satisfy the maximum allowable deflection and operate in optimum frequency response.

IV. CONCLUSIONS

The modeling of a micro-diaphragm has been presented. The simulation results are shown in Figures 1 to 7. It can be concluded that the large diaphragm radius and thin diaphragm increases the diaphragm deflection and diaphragm pressure sensitivity whilst decreases the diaphragm resonance frequency.

Diaphragm performance on diaphragm deflection, diaphragm pressure sensitivity, and resonance frequency are supported by analytical equations (1) to (6) and in agreeable with other researchers' findings [26-29].

Findings indicate that the diaphragm radius of 90μm and diaphragm thickness of 4μm are the optimum design parameters for the diaphragm to operate in frequency response and satisfy maximum allowable deflection.

ACKNOWLEDGMENT

This research is supported by Prime Minister's Department (66-02-03-0061/ORACLE 8150061) and PPP (PS055/2008A) grants.

REFERENCES

1. E. Cibula, D. Donlagic, C. Stropnik. "Miniature Fiber Optic Pressure Sensor for Medical Applications". *Applied Optics*, Vol. 44, No. 14, pp. 2736-2744, 2002.
2. G.C. Hill, R. Melamud, F.E. Declercq, A.A. Davenport, I.H. Chan, P.G. Hartwell, B.L. Pruitt. "SU-8 MEMS Fabry-Perot Pressure Sensor" . *Sensors and Actuators A:Physical*, Vol. 138, No. 1, pp. 52-62. 2007
3. R. Melamud, A.A. Davenport, G.C. Hill, I.H. Chan, F. Declercq, P.G. Hartwell, B.L. Pruitt. "Development of an SU-8 fabry-perot blood pressure sensor". *18th IEEE International Conference on Micro Electro Mechanical Systems*. Miami USA, 30 Jan – 3 Feb 2005. 2005
4. S. Nesson, *Miniature Fiber Optic Pressure Sensors for Intervertebral Disc Pressure Measurements in Rodents*. M.Sc. USA: University of Maryland, College Park. 2007.
5. M.J Madou. F*undamentals of Microfabrication The Science of Miniaturization*. 2nd Ed. CRC Press. 2002.
6. O. Tohyama, M. Kohashi, M. Sugihara, H. Itoh. "A Fiber-Optic Pressure Microsensor for Biomedical Applications". *Sensors and Actuators A*, Vol. 66, pp. 150-154. 1998.
7. K. Totsu, Y. Haga, M. Esashi. "Ultra-Miniature Fiber-Optic Pressure Sensor using White Light Interferometry". *Journal of Micromechanics and Microengineering*, 15, pp. 71-75. 2005.
8. S. Marco, J. Samitier, O. Ruiz, J.R. Morante, R. Esteve. "High Performance Piezoresistive Pressure Sensors for Biomedical Applications using Very Thin Structured Membranes". *Meas. Sci. Technol*. Vol. 7, pp. 1195-1203. 1996.
9. C. Pramanik, H. Saha, U. Gangopadhya. "Design Optimization of a High Performance Silicon MEMS Piezoresistive Pressure Sensor for Biomedical Applications". *J. Micromech. Microeng.*, Vol. 16, pp. 2060-2066. 2006.
10. J.B. Park, J.D. Bronzino. *Biomaterials Principles and Applications*.USA: CRC Press. 2003.
11. E. Cibula, D. Donlagic, Stropnik, C. "Miniature Fiber Optic Pressure Sensor for Medical Applications". *Applied Optics*, Vol. 44, No. 14, pp. 2736-2744. 2002.
12. G. He, F.W. Cuomo. "Displacement Response, Detection Limit and Dynamic Range of Fiber Optic level Sensors", *J. Lightwave Technol.*, Vol. 9, No. 11, pp. 1618-1625. 1991.
13. K.H. Shin, C.Y. Moon, T.H. Lee, C.H. Lim, Y.J. Kim. "Implantable Flexible Wireless Pressure Sensor Module". *Sensors and Actuators A: Physical*, Vol. 123, pp. 30-35. 2004.
14. C-C. Chiang, C-C K. Lin, M-S. Ju,. "An Implantable Capacitive Pressure Sensor for Biomedical Applications". *Sensors and Actuators* A, Vol. 134, pp. 382-388. 2007.
15. Y. Sun, G., Feng, G. Georgiou, E. Niver, K. Noe, K. Chin. "Center Embossed Design Guidelines and Fabry-Perot Diaphragm Fiber Optic Sensor", *Microelectronic Journal*, Vol. 39, pp. 711-716. 2008.
16. T.J. Tayag, K.S. Hoon, J. Marchetti, I.H. Jafri. "Optical Fiber Interferometer for Measuring the in situ Deflection Characteristics of Microelectromechanical Structures". *Opt. Eng*., Vol. 42, No. 1, pp. 105-111. 2003.
17. N. Pelletier, B. Beche, N. Tahani, L. Camberlein, E. Gaviot, A. Goullet, J.P. Landesman, J. Zyss. "Integrated Mach-Zehnder Interferometer on Su-8 Polymer for Designing Pressure Sensors." *Proceedings of IEEE Sensors*. 30 Oct – 3 Nov 2005.
18. H. Yu, L. Zhao. "An efficient denoising procedure for magnetic resonance imaging". *The 2nd International Conference on Bioinformatics and Biomedical Engineering*. Shanghai, China. 16-18 May, 2008.
19. J.H. Correia, M. Bartek, R.F. Wolffenbuttel, "Load-deflection of a Low Stress SiN-Membrane/Si Frame Composite Diaphragm". *Technical Proceedings of the 1998 International Conference on Modeling and Simulation of Microsystem*. USA. 1998.
20. N.A. Shirazee, A. Basak, T. Nakata, N. Takahashi. "Analysis of Permanent Magnet Lifting Devices using Finite Elements", *IEEE Transactions on Magnetics*, Vol. 33, No. 2, pp. 2211-2214. 1997
21. R.L. Goldberg, M.J. Jurgens, D.M. Mills, C.S. Henriques, D. Vaughan, S.W. Smith. "Modeling of Piezoelectric Multilayer Ceramics using Finite Element Analysis". *IEEE Transactions on Ultrasonics, Ferroelectronics and Frequency Control*, Vol. 44, No. 6, pp. 1204-1214. 1997.
22. J. Xu. *High Temperature High Bandwidth Fiber Optic Pressure Sensors*. Ph.D. Blacksburg, Virginia: Virginia Polytechnic and State University. 2005
23. J. Deng. *Development of Novel Optical Fiber Interferometric Sensors with High Sensitivity for Acoustic Emission Detection*. Dissertation submitted to Virginia Polytechnic Institute. 2004.
24. E. Madssen, P. Haere, R. Wiseth, "Radial Artery Diameter and Vasodilatory properties After Transradial Coronary Angiography". *Ann Thorac Surg*., Vol. 82, pp.1698-1703. 2006.
25. W. Osika, Dangardt, F.J Gronros, U. Lundstam, A. Myredal, M. Johansson, R. Volkmann, T. Gustavsson, L. M., Gan, P. Friberg. "Increasing Peripheral Artery Intima Thickness from Childhood to Seniority". *Journal of The American Heart Association*, 27(3), pp. 671-676. 2007.
26. M.D. Giovanni, *Flat and Corrugated Diaphragm Design Handbook* Marcel Dekker, Inc. 1982.
27. H.P. Le, K. Shah, J. Singh, A. Zayegh. "Design and Implementation of an Optimised Wireless Pressure Sensor for Biomedical Application" *Analog Interg Circ. Sig. Process*, 48, pp. 21-31. 2006.
28. X. Wang, B. Li, O.L. Russo, H.T. Roman, K.K. Chin, K.R. Farner,. "Diaphragm Design Guidelines and an Optical Pressure Sensor Based on MEMS Technique". *Microelectronic Journa,l* 37 . pp. 50-56. 2006.
29. N. Soin, B.Y. Majlis, "An Analytical Study on Diaphragm Behavior for Micro-machined Capacitive Pressure Sensor". *International Conference on Semiconductor Electronics*, 2002. Kuala Lumpur, Malaysia.