AC 2012-3563: DESIGN AND COMPUTATIONAL ANALYSIS OF DIAPHRAGM-BASED PIEZORESISTIVE PRESSURE SENSORS FOR INTEGRATION INTO UNDERGRADUATE CURRICULUM

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Design and Computational Analysis of Diaphragm Based Piezoresistive Pressure Sensors for Integration into Undergraduate Curriculum

1.0 Abstract

In order to expand undergraduate education in microelectromechanical systems (MEMS), and nanotechnology, a series of sensors were designed with the intent of integrating the design process into the project portion of a micro/nano systems course. The majority of the design work was focused around piezoresistive, diaphragm-based pressure sensors, utilizing multiple diaphragm sizes and geometries. These sensors were chosen for their geometrical simplicity and their ability to be manufactured using available photolithographic techniques. In order to gain a deeper understanding of the stress distribution in these sensors, leading to better design decisions, the Finite Element Analysis (FEA) technique was used. Results from this analysis were validated using analytical models available in the literature. Once this validation was accomplished, multiple iterations of FEA were performed in order to gain further understanding of the stress variation relative to diaphragm specifications. The results of these simulations were used to optimize the placement of the piezoresistors on the diaphragm and to assess the effect of process variation on the performance of the device. This analysis procedure aided in the design of pressure sensors with different sets of diaphragm geometries. The design and analysis procedures were documented and followed by students enrolled in the Nanosystems Engineering course to design and analyze the sensor type of their choice.

Keywords: MEMS laboratory, Nanotechnology education, Pressure Sensors

2.0 Introduction

The purpose of this study was to develop the procedure and streamline the steps for a design project within an undergraduate course, focusing on an introduction to Micro Electro-Mechanical Systems (MEMS), combined with nanotechnology. The decisions concerning the content of this course faced numerous challenges characteristic of an introductory MEMS course, as outlined by McAfee *et al.* [1]. These challenges include deciding which engineering disciplines should be allowed to take the course, what the prerequisites should be, what the respective roles of theory and practical experience should be, and whether a major project should be offered. It was decided that the course should be open to all engineering disciplines, available to fourth year undergraduates and graduate students, and to have a pre-requisite of a course covering the fundamentals of micro and nano-systems. Finally, it was decided that a design project was to be included to reinforce the analysis and manufacturing fundamentals taught in the course. The project included the design and analysis (both analytical and computational) of a sensor type of the students' choosing from amongst a proposed set by the instructor. The pressure sensor analysis documented here was used as a guide and example. Kaiser *et al.* documented a similar undergraduate project that included the analysis and manufacturing of a variety of different sensors with predesigned masks [2]. However, the intention of the project described here is to include the mask design as a portion of the project, and is of a narrower scope with regards to sensor types. Also, due to time constraints, the sensors designed as part of this project were not manufactured. Instead, pre-designed masks were built by students as part of a parallel project so that both design and manufacturing concepts were reinforced without the time limit inherent in performing them in series. The following provides details of the preliminary work performed by an undergraduate student to verify the design and analysis process which was used to generate materials for the course. Pressure sensors were chosen because of their simplistic geometry and wide spread use, and as such, information on the design and analysis of these sensors was readily available in the literature, and computational models were possible to simplify. Additionally, the simplistic geometry allows the sensors to be fabricated using available photolithographic techniques.

3.0 Pressure Sensor Design Selection

The two main types of pressure sensors are piezoresistive sensing and capacitive sensing. Piezoresistive sensing takes advantage of the piezoresistive effect, found in some materials, which is characterized by the change of resistivity of a material caused by an applied stress. The main advantage of this method is high sensitivity particularly when using silicon. In addition, this method can be easily implemented using standard lithographic techniques. The disadvantages of this method are that piezoresistors are sensitive to temperature changes and crystallographic direction. [3].

Capacitive sensors are based on the varying distance between two thin conductive plates relative to an applied deflection. This method is less sensitive to environmental conditions than the piezoresistive method, but is more analytically complex and requires additional manufacturing steps. [3]. Considering these facts within the design and build decisions, the piezoresistive method was chosen over the capacitive method.

3.1 Piezoresistive Pressure Sensor Analysis

The most common piezoresistive pressure sensor is based on a thin membrane – a diaphragm – with four embedded piezoresistors. The thin diaphragm is created by etching a cavity into a supporting material, usually silicon and piezoresistors are then diffused into the surface of the diaphragm. When a pressure is applied to the diaphragm, a stress is produced that translates into a change in resistance of the piezoresistors. By measuring the change in resistance, the applied pressure can be found. Figure 1 shows a schematic of a basic diaphragm based pressure sensor deflecting under an applied pressure [4]. This basic type of pressure sensor can be produced using a variety of different geometries for the diaphragm. The two most common are square and circular diaphragms. It is important to know the locations of the maximum stress and the point of failure. Equations 1 and 2 can be used to determine the

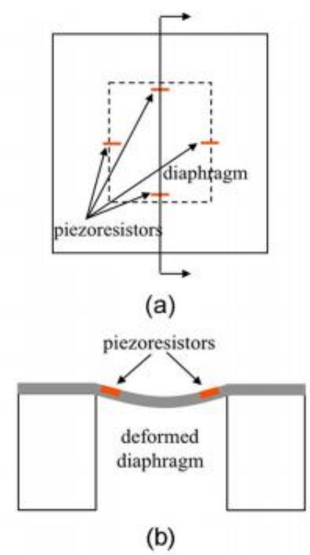

Figure 1 Example of a pressure sensor with piezoresistors oriented in both the transverse and longitudinal directions from (a) top and (b) section views [4].

maximum radial and tangential stresses in a circular diaphragm, which are located at the outer edge of the diaphragm [3]. The tangential stress is simply related to the radial stress by Poisson's ratio.

$$Maximum\ Radial\ Stress = (\sigma_{rr})_{max} = \frac{3pd^2}{4t^2} \tag{1}$$

$$Maximum\ Tangential\ Stress = (\sigma_{\theta\theta})_{max} = (\sigma_{rr})_{max} * \nu \tag{2}$$

where d is diameter, t is thickness, and p is the applied stress. Poisson's ratio (ν), can be approximated as 0.17 for monocrystalline silicon when considered isotropically [5]. The radial and tangential components of stress were combined by vector addition, and it was assumed that the shear stress at the surface of the diaphragm is negligible [3]. This relationship is shown in Equation 3 and will be used for further analysis of the maximum combined stress in the diaphragm in order to estimate the point of failure.

$$\sigma = \frac{3pd^2}{4t^2}(1 + \nu^2)^{1/2} \tag{3}$$

As shown in Equation 3, the stress induced in the sensor is a function of the applied pressure and the geometry of the diaphragm. Accordingly, the factors of the measurable stress that can be controlled via the design and manufacturing of the sensor are the diaphragm diameter and thickness. Both of these factors have a similar effect in that they both have a squared (or inverse squared) relationship with stress. However, the local effects of each parameter must be considered. Because the thickness of the diaphragm is usually much smaller than the diameter, a small change in the thickness will affect the overall stress in the diaphragm much more than an equal change in the diameter. For the chosen design, the difference between the diaphragm thickness and diameter will be, approximately, an order of magnitude. Therefore, the effect on the stress in the diaphragm due to a change in the thickness is about two orders of magnitude larger than a comparable change in the diameter. Subsequently, because the tolerance of the thickness dimension is approximately an order of magnitude greater than that of the diameter (based upon the different manufacturing techniques to create them), the actual difference in stress in the diaphragm is approximately one order of magnitude.

In addition to determining the maximum stress in the diaphragm, understanding the stress distribution across the entire surface is desirable to assist in the placement of the piezoresistors. The process used for aligning the piezoresistors with the edges of the diaphragm has some inherent variability, so understanding the change in stress across the diaphragm is necessary in order to understand how the stress in the sensor diaphragm will change with placement error.

The theoretical solutions for the stress in a membrane with a uniform applied stress are extremely complex [3]. In order to get a general idea of the stress distribution in the diaphragm, computational techniques were employed. First, Computer Aided Design (CAD) software was used to create a simplified representation of the sensor membrane. The Finite Element Analysis (FEA) technique was then applied to the model. This technique divides the solid model into a number of small elements to which stress and strain relationships are numerically applied, subject to boundary conditions applied to the solid. In order to verify the trends identified with the FEA, a simple experiment was designed where the thickness of the diaphragm was varied from 5 to 50 μm, with all other variables held constant, and the overall trend was compared to the solution of the analytical model for a circular diaphragm. The maximum principal stress for each thickness value was recorded, and then all of the values were normalized to the applied pressure. The results are shown with a fitted curve in Figure 2. The curve showed good correlation with an exponent close to the expected value of -2 which matches the result found using the analytical solution.

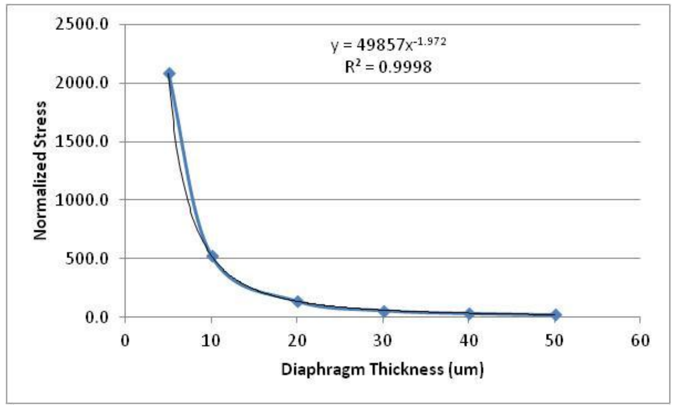

Figure 2: Normalized stress as a function of diaphragm thickness.

Using this data it is possible to visualize the localized change in stress as a function of the diaphragm thickness by taking the derivative of the curve in Figure 2. Figure 3 shows this relationship graphically. It is apparent that for small diaphragm thickness, a slight change in the thickness results in a very large change in the stress (more than 800 times the applied stress at a diaphragm thickness of approximately 5 μm), while as the thickness becomes larger, the effect of small thickness variations on the stress becomes negligible.

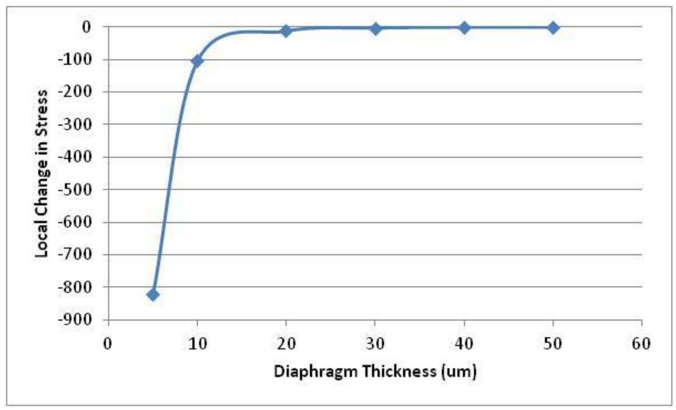

Figure 3: Localized change in stress as a function diaphragm thickness

Figure 4 shows a contour plot of the von Mises stress produced in a circular diaphragm under a uniform applied pressure. This verifies that the maximum stress is located at the outer edge of the diaphragm. The stress in the diaphragm is radially symmetric, showing a minimum approximately halfway between the center and the edge of the diaphragm, shown as a blue ring in the contour plot. Figure 5 shows a graph of the von Mises stress across a diameter of the circular membrane. This graph shows that the minimum stress occurs at a distance from the edge equivalent to approximately 20% of the length of the diaphragm. Therefore,

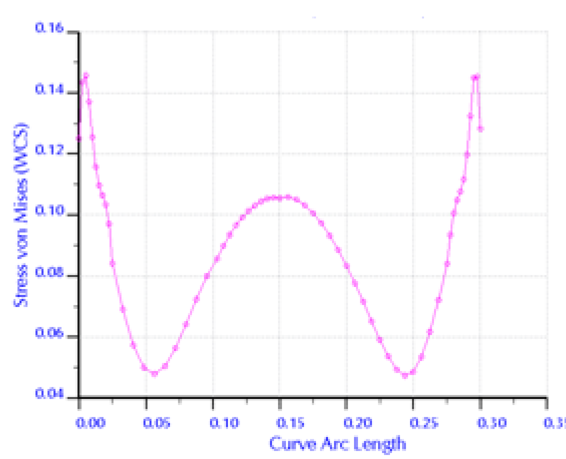

Figure 4: Graph of the von Mises stress across a diameter of a circular membrane subjected to a uniform applied pressure.

maximum sensitivity of the sensor will occur when the piezoresistors are located directly over the outer edge of the diaphragm, while the minimum sensitivity will occur if the piezoresistors are located at a distance from the outer edge approximately equal to 20% of the diaphragm length.

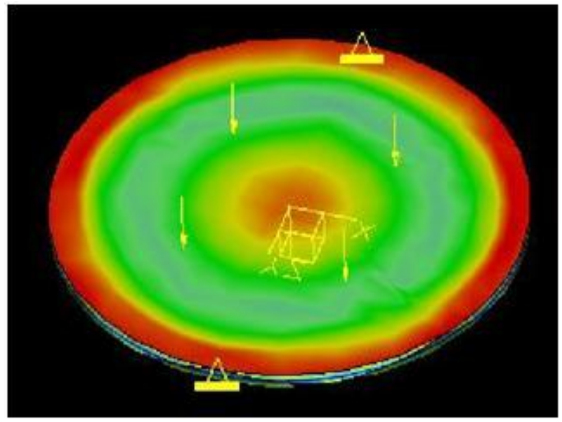

Figure 5: Contour plot of the von Mises stress in a circular membrane under a uniform applied pressure.

The analytical solution for the maximum pressure for a square diaphragm, which is located at the center of the outside edges, is given by Equation 4.

$$\sigma_{max} = \frac{0.308pa^2}{t^2} \tag{4}$$

where a is the edge length, t is the diaphragm thickness, and p is the applied pressure. Notice that this equation is very similar to the analytical equation for the maximum stress in the circular diaphragm, although the coefficient is smaller. Therefore, as compared to a circular diaphragm with the same characteristic length (diameter vs. edge length) the circular diaphragm will have a larger maximum stress for the same applied pressure, and subsequently, will be more sensitive, but will also have a lower threshold before fracturing.

The same FEA was performed on a square diaphragm. Figure 6 shows the contour plot of the von Mises stress and a graph of the von Mises stress across the center of the diaphragm. The FEA confirms that the maximum stress is located at the center of the outside edge and that the stress distribution across the center is similar to that of the circular diaphragm. Therefore, similar conclusions can be made about the placement of the piezoresistors in that they should be located as near to the edge as possible for maximum sensitivity while avoiding the minimum stress point about 20% of the side length away from the outside edge.

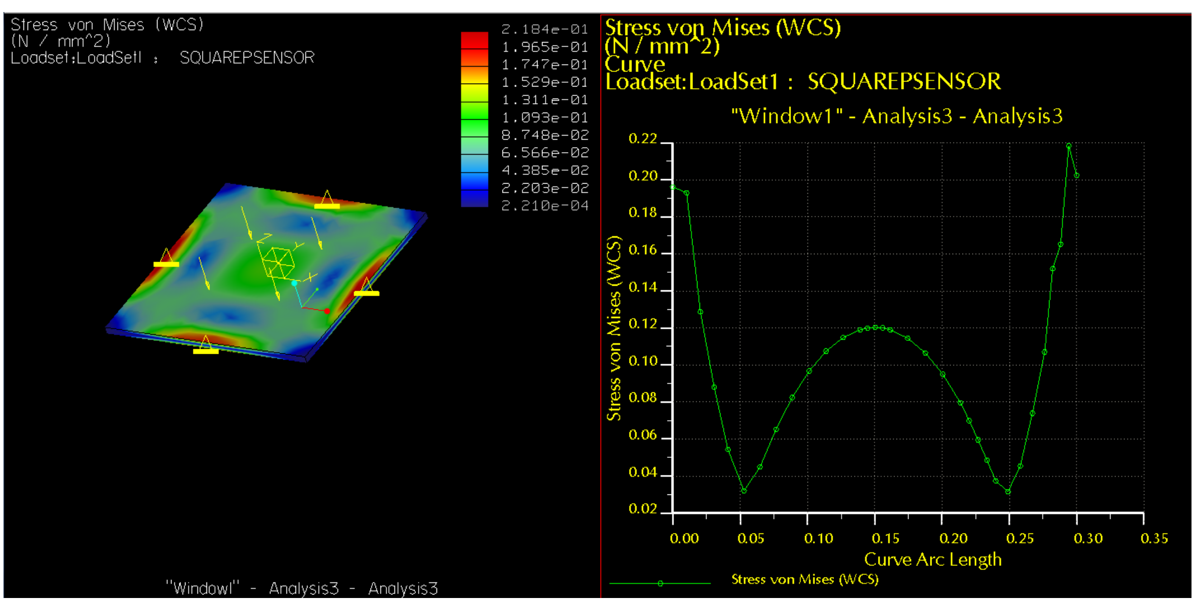

Figure 4: FEA results of square diaphragm subjected to a uniform pressure load.

Using this analysis, a tutorial was created for instructional purposes that explained in detail how to create the CAD model and how to properly configure the FEA. This material was useful as many students were several years removed from a required CAD course or had never used this particular software package or worked with FEA. This was especially a concern considering the wide variety of disciplines and skills of the students enrolled in the course.

3.2 Design Decisions

The following design decisions needed to be made: the number of sensors per wafer, the geometry of the sensors, the maximum pressure that the sensors can sustain, and the orientation of the sensors.

It was decided to make multiple sensors on the same wafer in order to achieve a variety of sensitivities. Because all of the sensors are meant to be manufactured on the same wafer, the thickness of the diaphragms will be identical. Therefore, the characteristic length (diameter and edge length) of the sensors will be varied. Three circular sensors and three square sensors were designed with characteristic lengths of 200, 300 and 500 μm, respectively. The thickness was selected to be 10 μm.

Given these parameters, it is desirable to determine the maximum pressure that each sensor can sustain before fracture. Because these sensors are to be manufactured from single crystals, it is assumed that the yield strength of the material is equivalent to the fracture strength. The fracture strength of monocrystalline silicon has been found to be 7000 MPa [6]. However, this strength is rarely observed in diaphragm based sensors, rather, the actual strength of the material is approximately 300 MPa [7]. This difference is caused by stress concentrations produced by the extremely sharp inside corners inherent to anisotropic wet etching [7]. This issue can be mitigated through the use of an additional isotropic etching procedure, but because this process will not be used in the manufacturing of these devices, a strength of 300 MPa will be used for all calculations. By solving Equations 3 and 4 for the pressure, substituting the stress term with the yield stress of the material, the maximum pressures for each sensor type and size for a thickness of 10 μm are found, which are listed in Table 1. These pressures are relatively high, especially for the square pressure sensors. It is unlikely that stresses high enough to fracture the diaphragms will be encountered during standard testing.

Table 1: Maximum pressures before failure of circular and square diaphragm pressure sensors with varying characteristic lengths.

Characteristic Length (μm)	t = 10 μm	
	Max Pressure (kPa)	
	Circular	**Square**
200	986	2435
300	438	1082
500	158	390

Because p-type silicon wafers were readily available and were to be used for this project, the piezoresistors must be composed of n-type silicon. Therefore, to obtain maximum sensitivity of the sensor, the piezoresistors and the sensors had to be oriented along the <100> family of directions. This direction is at a 45^{o} angle to the primary wafer flat.

4.0 Adoption, Assessment, and Lessons Learned

Through the work done in this study, two sets of materials were prepared for an undergraduate course on MEMS and nanotechnology. The first was documentation on the design process and the second was a tutorial for generating the CAD model and performing the FEA. These materials were critical to overcome both challenges of: (i) fitting a lot of work into a very limited amount of time, and (ii) teaching students with different backgrounds such a highly interdisciplinary topic. These material were used for the portion of the course in which students were allowed to select a sensor type to design and analyze. The class was divided into teams of two students each who picked a device to design up to the mask design level. The design process documentation provided an outline for the students to follow in the design of their own sensors. Having a procedure to follow through this process helped the students significantly in rationalizing their design decisions while taking into consideration the manufacturability aspects of the process. In addition, having a procedure to compare to helped in cutting the design time and quickly converging onto a final mask design. Due to limitations of time and equipment, students were not able to build and test their selected sensors, and instead manufactured wafers with different devices using available masks. However, the transition was smooth as the focus was always on the concepts and the application procedure, not on the particular device at hand.

The CAD and FEA tutorial was necessary because many of the students had only limited experience with CAD or FEA (e.g. EE students), or had not used the particular software platforms available. This tutorial provided aid in applying the interdisciplinary concept of engineering and emphasized the idea that MEMS and Nanotechnology is not a singular science or engineering discipline, but rather an interdisciplinary platform of knowledge.

Students were assessed directly on their ability to apply the learned concepts and procedures in class and during their hands-on activities, aided by these tutorials. All students in the class managed to produce final mask designs which were checked by the instructor and deemed valid. These designs will be sent to an external facility to produce the relevant masks. Students were also assessed directly on their ability to follow the manufacturing procedure when masks are provided and all students passed this part successfully, and in the allotted time.

Indirect assessment showed through students' feedback that the experience was generally positive. In particular, the CAD and FEA tutorial was useful for EE students that had not used CAD extensively and had never performed an FEA. The design documentation of an example pressure sensor provided them a valuable frame of reference considering the lack of many parts of knowledge in this area based on their traditional undergraduate education. As part of their constructive criticism, students expressed their desire to have more time for manufacturing devices in the cleanroom. They also thought that it would be more effective if they had the chance for exposure to more MEMS and nanotechnology based devices.

5.0 Conclusion

For use in an introductory MEMS course for senior undergraduate engineers, a project was created in which diaphragm based pressure sensors were designed and analyzed, both analytically and computationally. This study documented the initial work performed in order to construct materials for the course. The result of this study was an example mask design for pressure sensors with two different geometries (circular and square diaphragms), manufacturing process steps that implement available lithographic techniques, and a tutorial for the CAD design and finite element analysis of these sensors. In preparing these materials, the diversity of skills inherent to including engineering students from multiple disciplines was accounted for, and an understanding of the prerequisites was considered in order to create materials appropriate for all of the student likely to enroll in the course. Now that the pre-course experience and the pilot run of the course experience are both available, with some assessment data, the next course offering can be improved significantly. The designs of devices up to the mask designs will be sent for manufacture and used as actual samples for students to investigate. Time in the cleanroom to manufacture devices would be planned for possible expansion outside lab time. Knowledge gaps inherent with students are more known now and can be treated within the course, through pre-requisites of the course, or by collaborating with instructors of common courses which precede this course but are common to most students in engineering.

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