Robust Design of Silicon Piezoresistive Pressure Sensors

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ABSTRACT

In order to analyze silicon piezoresistive pressure sensors, several methods are used to obtain the stress distribution for different sizes and configurations of square diaphragm type silicon pressure sensors. Furthermore, through integral considerations and thoughtful arrangements, the whole device nonlinearities (including the nonlinearities caused by piezoresistive relations and die structure) and output voltage (varied due to different dimensions and locations of piezoresistors) can all be calculated accurately.

The Taguchi method then is adopted to help achieve optimal design based on the developed CAD tool. It helps us understand more about the effects of chosen parameters as well as achieve a better design.

It is anticipated that this design method and tool will be further extended to other types of piezoresistive pressure sensors in the future and help shorten the design cycle time and development costs effectively.

Keywords: pressure sensor, simulation, robust design, CAD

INTRODUCTION

Designers of micromachined silicon pressure sensors have tried to evaluate the performance of new designed devices effectively before putting into mass production. Yet the available design tools are rare. Some commercial software companies (e.g., MEMCAD by Microcosm, IntelliCAD by IntelliSense) are trying to develop Computer Aided Design (CAD) tools for MEMS. However, these softwares are still far from being useful for this purpose most of the time, special purpose CAD is still developed in-house.

Basically, the bottlenecks of silicon micro pressure sensor lie in the areas of structural design and process. This study tried to achieve the optimization in structure by approaching from structural design. Since we are concerned about the optimization, the objectives must be clearly defined. Generally speaking, linearity and output voltage (also expressed as sensitivity) are the two main criteria to evaluate the performance of silicon micro pressure sensors. But these two criteria usually conflict with each other, i.e.; it is hard to achieve targeted values at the same time. However, the tolerance of voltage output range is usually larger than that of the linearity range, so the linearity is set as the main target to improve.

The sources of linearity mainly come from (1) the nonlinearity of piezoresistive relationship (2) the nonlinearity of die structure itself (3) the nonlinearity of Wheatstone Bridge. Besides those effects, the device output can also be influenced due to silicon thermal sensitivity and silicon repeatability and hysteresis itself. It can be seen that the nonlinearity is contributed from a lot of sources. A compensation circuit will become too complicated and impractical. However, a well-designed structure will help reduce the unwanted linearity problems. We will concentrate on the first two sources of nonlinearity since they are dominant factors.

The linear piezoresistive relationship is usually used to explain and design the piezoresistors of silicon pressure sensor. But in real life, the relation between stress and resistivity change is not linear. The nonlinear phenomenon is first studied by K. Yamada [1] on silicon pressure sensor of circular diaphragm. Later, K. Suzuki [2] completed the study on square diaphragm silicon pressure sensor. Generally speaking, a third order polynomial is sufficient to describe the system.

The nonlinearity of die structure is mainly due to the large deformation. This can be explained by using a "plate" model. Basically, a plate can be modeled as (1) a small deformation thin plate [3] (2) a large deformation thin plate (3) a thick plate. The diaphragm of silicon pressure sensor can be treated as case (2). The inner plan elongation of diaphragm due to outside overpressure will cause large deformation. This is usually called balloon effect. In this paper, an analytic model for a thin plate under small deformation is considered first and some insights are built. In order to further study the nonlinearity due to the large deformation of the diaphragm, Finite Element Analysis is used to help study the effects. ANSYS version 5.2 with its submodeling capability is chosen as the kernel for the CAD tool. Furthermore, the nonlinearities contributed by the nonlinear piezoresistive relation are also considered. It can be seen that the contributions of the above effects are not negligible. In addition to the width and thickness of diaphragm, the size and location of resistors will also influence the performance of such device due to the effects of stress gradient. Therefore, the above parameters will set as the main consideration.

After developing the CAD tool, designing a "better" device is obviously the next goal. The Taguchi method, a well-known robust design method in the industry, is adopted for this purpose. After reviewing the process carefully, four parameters are chosen to do the robust design. It will help us understand more about the effects of these parameters as well as achieve a better design.

NONLINEAR PIEZORESISTIVE RELATIONSHIP

Since piezoresistive pressure sensor has been studied for a long time [4-6], its properties will be only briefly introduced here. For convenience, the resistance change in a piezoresistor is usually expressed linearly as

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \tag{1}$$

where σ_l and σ_t are the longitudinal and transverse stress on piezoresistors respectively, and π_l and π_t are the longitudinal and transverse piezoresistive coefficients (depending on crystal direction of piezoresistors) respectively.

K. Suzuki etc. further consider the nonlinear resistor change on square diaphragm and it can be expressed as

$$\frac{\Delta R}{R} = \sum_{i=1}^{n} (C_{li} \sigma_l^i + C_{ti} \sigma_t^i) \tag{2}$$

where C_{li} and C_{ti} are the ith longitudinal and transverse coefficients respectively. Generally speaking, a third order polynomial, i.e., n=3, is sufficiently to describe the system. It should be noted that the stress in this formula includes membrane stretching stress and it is the main cause of nonlinearity.

THIN PLATE THEORY

It is known from thin plate theory that when a square plate with width 2a and height h is under pressure q, its deflection can be approximated as

$$w = q\frac{12a^2}{Eh^3}(1-\nu^2)(1-\frac{x^2}{a^2})^2(1-\frac{y^2}{a^2})^2[0.0202 + 0.0054(\frac{x^2+y^2}{a^2}) + 0.0063(\frac{x^2y^2}{a^4})] \tag{3}$$

$$\sigma_x = \frac{-Eh}{2(1-\nu^2)}(\frac{\partial^2 w}{\partial x^2} + \nu\frac{\partial^2 w}{\partial y^2}) \tag{4}$$

$$\sigma_y = \frac{-Eh}{2(1-\nu^2)}(\frac{\partial^2 w}{\partial y^2} + \nu\frac{\partial^2 w}{\partial x^2}) \tag{5}$$

It can be found that the maximum stress is located at the center of edge. Since the surface of silicon wafer is usually a (100) plane and the edge of anisotropic fabricated square diaphragm is in <110> direction. If p-type resistors are put along and perpendicular to <110> direction on a n-type (100) silicon square diaphragm respectively, the resistance change can be shown approximately as

$$\frac{\Delta R}{R}_{pl} = -\frac{\Delta R}{R}_{pp} \cong \frac{\pi_{44}}{2}(\sigma_l - \sigma_t) \tag{6}$$

where $(\Delta R/R)_{pl}$ and $(\Delta R/R)_{pp}$ represent the resistance change of parallel and perpendicular resistors respectively.

From the calculation, it can be found that the maximum resistance change appears in the center of edges and is around

$$\frac{\Delta R}{R} = 0.56\pi_{44} q \frac{a^2}{h^2} \tag{7}$$

Minimum resistance change appears in the center of plate and equal to zero. Therefore, it can be seen that resistance change is proportional to (a^2/h^2). In order to increase the sensitivity of the device, the length a needs to be increased and thickness h decreased.

SENSITIVITY

The above equations can be further extended to the stress change on resistors. Since the length of resistor is finite and the above stress equations are function of position, the integral can be used to solve this problem.

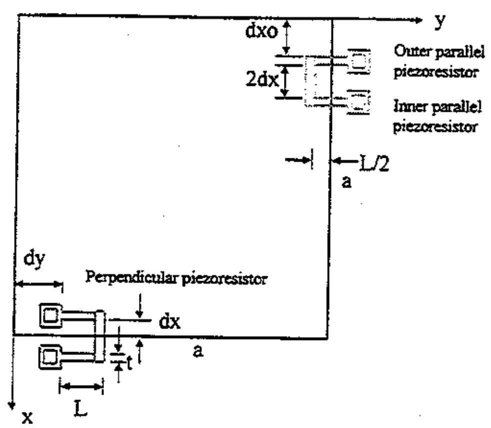


Figure. 1 The positions of the piezoresistors in a 1/4 square diaphragm

It is known that the location and shape of resistors will influence the effects of pressure sensors. Therefore as shown in Figure (1), the resistors are usually put in the regions where stress is larger to increase the sensitivity. To reduce the stress gradient, the resistors are broken into two parts. The length of resistors, L, and width, t, are the important parameters for shape. The distance between outer parallel resistor and diaphragm edge is dxo, and between inner parallel resistor and diaphragm edge is 2dx+t. The distance between perpendicular resistor and diaphragm edge is dy. Then the stress of outer parallel resistor can be expressed as

$$\sigma_{x,plo} = \frac{\int_{a-L/2}^{a}\int_{dxo}^{dxo+t}\sigma_x dxdy}{Lt/2} \qquad (8)$$

$$\sigma_{y,plo} = \frac{\int_{dxo}^{dxo+t}\int_{a-L/2}^{a}\sigma_y dydx}{Lt/2} \qquad (9)$$

where $\sigma_{x,plo}$ and $\sigma_{y,plo}$ are the stress of outer parallel resistor along x and y axes respectively. It can be seen that as the resistor becomes longer, the actual stress shown on resistor may become lower.

Similarly, the stress of other resistors can be found. If all resistors are exactly the same and no zero offset is considered, then the sensitivity can be approximated as

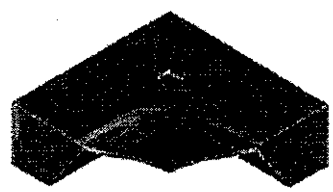
$$s = \left(\frac{1}{2}\frac{\Delta R}{R}_{pl} - \frac{1}{2}\frac{\Delta R}{R}_{pp}\right) \qquad (10)$$

where $(\Delta R/R)_{pl}$ and $(\Delta R/R)_{pp}$ represent the resistance change of the parallel resistor and the perpendicular resistor respectively.

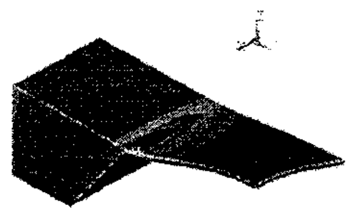
From the above equations, the output and nonlinearity can also be calculated.

FINITE ELEMENT ANALYSIS

However, the above thin plate theory is good only when the deflection is small compared with thickness of diaphragm. Therefore, the real application is limited. Though the theory for thin plate with large deformation has been developed, the solution can not be obtained easily. Finite element analysis is obviously the best candidate to serve this purpose. Since the dimension of resistors is too small compared with the real dimension of die, a meaningful mesh will need a very large database and long calculation time. Meanwhile, large deformation asks for nonlinear calculation and strict convergence problem. Therefore, the submodeling technique provided in ANSYS, which requires less storage space and still provides needed mesh size, is used. The submodeling process requires to create a new small model out of the original model (that's why it is called submodel) and read in the boundary conditions of cutting edge with previous larger model.



$\sigma x-\sigma y$ (1/4 of die model)



$\sigma x-\sigma y$ (New submodel)

Figure 2. Stress distribution under pressure

In order to reduce the developing time and help study the system behavior, a CAD system for studying pressure sensor is built on ANSYS [7]. This CAD system is mainly developed to do the submodeling and adding boundary conditions automatically. The parameters listed on Figure (1) are the main input variables. Figure (2) shows one of results (σ_x-σ_y) on a one-fourth square diaphragm and its submodel. It can be seen that the stress distribution, (σ_x-σ_y), are shown symmetrically on the center of edge with different signs. This strategy makes the output of Wheatstone bridge larger.

Just showing the stress distribution will not help us to evaluate the system performance. In order to build a useful CAD system, the linearity and Wheatstone bridge output should be able to be calculated. Furthermore, the nonlinearity contributed by piezoresistive relationship and die structure should be considered at the same time. Like the one shown in previous section, the stress distribution relations from Finite Element Analysis are incorporated to get real stress on each resistor to obtain the desired linearity and Wheatstone bridge output. A useful CAD system is thus built to help us design future sensors and improve our current design.

ROBUST DESIGN

In order to improve our current design, Taguchi method and our CAD system are used to help us obtain a robust design. The configuration as shown in Figure (3) is used. The thickness of diaphragm is not used for process consideration in this case though it is a major factor. It can still be compared in future study. Different methods are used to calculate the results and sometimes the results are quite different. One is thin plate theory for small deformation and done in MathCad. The others are Finite Element Analysis with small deformation (linear) and large deformation (nonlinear) options. The results are shown in Figures (4)—(7). Figure (8) shows the comparison between simulation results by using Finite Element Analysis with large deformation and experimental result for the nine configurations listed in Figure (3). Since there exists the accuracy problem about measuring thickness, the thickness of 15 and 17 micron are used for doing simulations. It can be seen the trend of both experimental and simulation results matches well. The results are also quite close.

Orthogonal arrays (L_9) used in analysis

	a(um)	t(um)	dxo(um)	dy(um)
1	500	8	25	5
2	500	12	50	10
3	500	16	75	25
4	600	8	50	25
5	600	12	75	5
6	600	16	25	10
7	675	8	75	10
8	675	12	25	25
9	675	16	50	5

a : Diaphragm Dimension

t : Width of Bridge Resistor

dxo: Distance of Resistor to Diaphragm (X Axis)

dy : Distance of Resistor to Diaphragm (Y Axis)

Figure 3. Orthogonal arrays (L_9) used in analysis

After using response table and additivity, a new configuration for our sensor is chosen. The performance is quite good. For example, the linearity error improved from original around 2% to current 0.5%.

CONCLUSIONS

A CAD system is first successfully developed for predicting linearity and sensitivity of piezoresistive pressure sensor. Three methods of estimation are also compared for different configurations. Based on the developed systems and robust design methods, the design optimization has been achieved to improve both of the sensitivity and linearity of pressure sensors.

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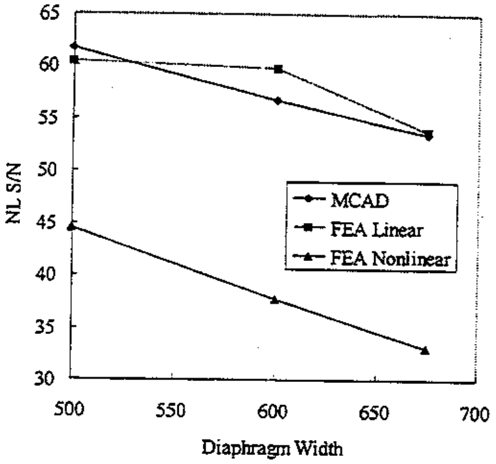

Figure 4. Linearity S/N ratio vs. diaphragm width

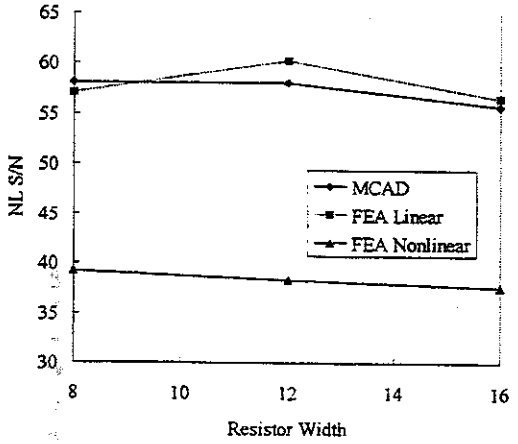

Figure 5. Linearity S/N ratio vs. resistor width

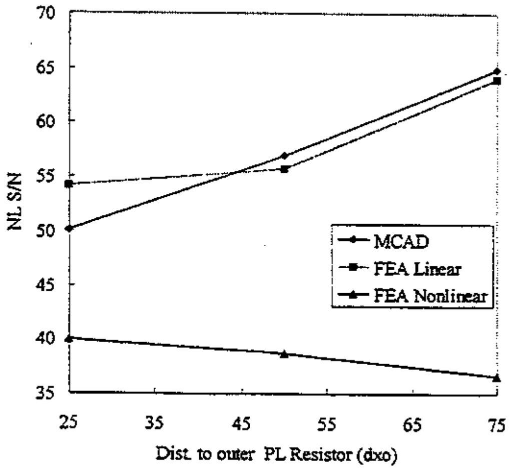

Figure 6. Linearity S/N ratio vs. dxo

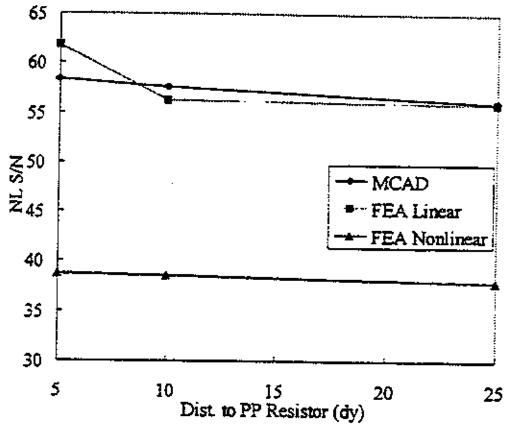

Figure 7. Linearity S/N ratio vs. dy

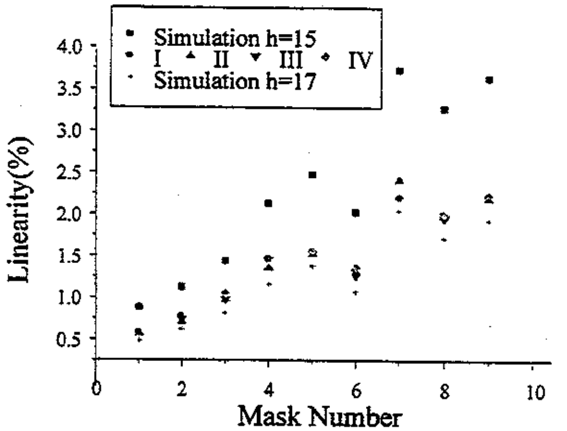

Figure 8. Comparison between simulation and experimental data