

# Design and Fabrication of MEMS Multi-sensor

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**Abstract**—A single mask-set was designed and implemented into the RIT bulk MEMS process in order to create multiple piezoresistive MEMS sensors. These sensors included a MEMS accelerometer, pressure sensor and flow sensor. Sizes of 9mm<sup>2</sup>, 36mm<sup>2</sup>, 81mm<sup>2</sup> were included in the design. Using this integration, the difference between the sensors was the utilization of the piezoresistive properties of the thin diaphragm with polysilicon resistors by different packaging and off chip electronics. In the gas flow sensor the resistor lengths and resistances induced a voltage change by flow of a liquid over the diaphragm. In the accelerometer, the resistors changed by a force on the diaphragm measured by a test cantilever. In the pressure sensor the resistors will change dimensions by the strain induced a force induced by air pressure on the diaphragm measured by a power supply detecting output voltage

**Index Terms**—piezoresistive

## I. INTRODUCTION

PIEZORESISTIVE sensors have a large range of applications in areas such as biomedical, military, automotive. The sensitivity and design depend on their specific application. In order to obtain high sensitivity in a small range of pressures, flows and the diaphragm is usually weaker than those with a larger pressure range because of the force that the area of the material must withstand. In this case a silicon pressure sensor was chosen for its electrical and mechanical properties because not only is it a semiconductor and can be doped for certain electrical properties, but it is also a very strong material.

MEMS fabrication can be costly and time consuming; however by creating a single fabrication design that can yield three different sensors, the manufacturing costs can be decreased. This goal of this project was to create a mask design that makes it possible to create a MEMS accelerometer, pressure sensor and flow sensor in one design. After the fabrication, they were packaged to become one of three choices, which involve different packaging and off-chip electronics. This design therefore becomes more flexible from a manufacturing standpoint.

## II. THEORY AND DESIGN

### A. Diaphragm

In this design, a piezoresistive sensor is created by implementing the use of a thin diaphragm, which senses tensile or compressive stress. The stress in the diaphragm,  $\sigma$ , is

shown by (1), but to calculate this, we must first calculate L,H. The length, of the diaphragm is defined by the KOH etch which etches at 54.7° on (100) Silicon with an initial length design of 3000μm thickness of ~300μm. The following equations illustrate the design of the 9mm<sup>2</sup> device. These equations and calculations are shown in (2),(3).

$$\sigma_{diaphragm} = .3 \left( P \left( \frac{L}{H} \right)^2 \right) = E_{Si} \epsilon \quad (1)$$

$$L_{actual} = L_{mask} - 2 \left( \frac{t_{sub} - t_{diaphragm}}{\tan(54.7^\circ)} \right) \quad (2)$$

$$L_{actual} = 3000 \mu m - 2 \left( \frac{300 \mu m}{\tan(54.7^\circ)} \right) = 2828.25 \mu m \quad (3)$$

The corresponding thickness, H, of the diaphragm is designed for 20-30μm using end point detection in the KOH etch. The Young's Modulus, E, for Silicon is 1.9E11 N/m<sup>2</sup>. With these parameters the stress calculation is shown in (4). The resulting strain is calculated in (5).

$$\sigma_{diaphragm} = .3 \left( 103 \times 10^3 \frac{N}{m^2} \left( \frac{2828.25 \mu m}{25 \mu m} \right)^2 \right) = 3.96 \times 10^8 \frac{N}{m^2} \quad (4)$$

$$\epsilon = \frac{\sigma}{E_{Si}} = \frac{3.96 \times 10^8 \frac{N}{m^2}}{1.9 \times 10^{11} \frac{N}{m^2}} = .2082\% \quad (5)$$

### B. Photomask Design

In a square diaphragm, shown in figure 1, the stress is greatest in the middle of each side of the square, which is where the resistors, in red, are placed. The purple box represents the diaphragm at 3000μm x 3000μm. The calculated length is 2828μm x 2828μm. The goal is to have the resistors placed on the edge of the diaphragm at the maximum points of stress in order to have the greatest sensitivity. This is so that the strain produced induces a large change in the length of the resistors, resulting in a higher change in voltage. The arrows on Figure 2 illustrate the direction of the strain when a pressure is applied to the center of the diaphragm. In the accelerometer a proof mass was added when testing in order to increase the sensitivity.

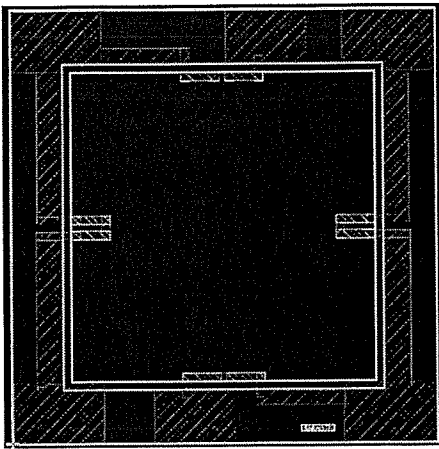


Fig. 1. Pressure sensor mask design created in IC Station

The top and cross sectional view of the sensor created by this design is shown in Figure 2.

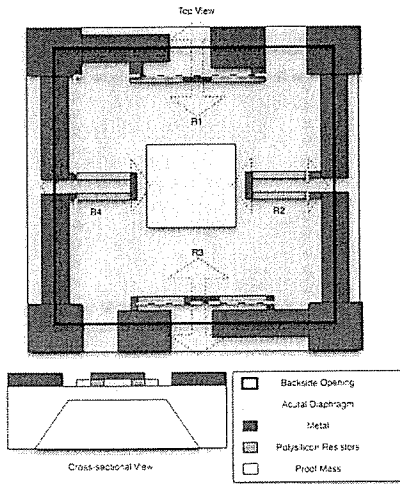


Fig. 2. Multi-sensor Top View and Cross Section

To implement the pressure sensor nothing would be added to the diaphragm to increase sensitivity. For an accelerometer a proof mass would be added to the diaphragm, shown in figure 2, in order to obtain a greater output voltage from the oscillations of the cantilever test setup. Lastly, to detect flow, a taller sail with less mass would be fixed to the diaphragm in order to obtain a greater output voltage from flow of a liquid over the diaphragm in a sealed tube.

### C. Resistor Design

Assuming a polysilicon sheet resistance of 61 ohms/square and equal resistances (without strain), a design of 12 squares was chosen. This results in a theoretical 366 ohm resistance that must be multiplied by 2 to account for the fact that each resistance (R1-R4) is made up of two of these resistors which is 732 ohms. The formula and calculation are shown in equations 6,8. As we do not have an exact measurement of our polysilicon sheet resistance that the LPCVD will deposit, we have a rough estimate. Since the resistances R1-R4 are comprised of two resistors connected in series, where R1,R4 are designed end to end and R2,R3 are laid out side by side.

Due to the way the resistors are placed in the design, shown in figure 1, the strain will affect each resistance differently. Resistances R1,R4 will increased by the strain in the length and R2,R3 will be decreased by a strain in the Width. Equations (7),(9)-(13) show these respective calculations for new L', W' that were increased by the strain in the diaphragm. In the end, these are very small changes in resistances compared to the change that will occur if the sheet resistance ends up being significantly different.

The equation in (6) shows the resistance calculation used in the polysilicon resistors.

$$R = R_s \left( \frac{L}{W} \right) \quad (6)$$

When factoring in the strain from diaphragm in the L direction the equation in (7) is used and likewise equation (8) is used for the W direction.

$$R_L = R_s \left( \frac{L + \epsilon L}{W} \right) \quad (7)$$

$$R_W = R_s \left( \frac{L}{W + \epsilon W} \right) \quad (8)$$

When the polysilicon resistors are under no stress they should all be at their nominal values which are calculated in equation (9).

$$R_{no\ stress} = 61 \frac{\Omega}{sq} \left( \frac{360 \Omega}{60 \Omega} \right) = 366.75 \Omega (2) = 732 \Omega \quad (9)$$

The change in length and width due to strain in this design are shown in (10) and (11).

$$L' = 360 \Omega + (360 \Omega \cdot .00208) = 360.75 \Omega \quad (10)$$

$$W' = 60 \Omega + (60 \Omega \cdot .00208) = 60.13 \Omega \quad (11)$$

Factoring these changes in resistance to the design gives use (12) and (13).

$$R_{1,4} = 61 \frac{\Omega}{sq} \left( \frac{360.75 \Omega}{60 \Omega} \right) = 366.763 \Omega (2) = 733.53 \Omega \quad (12)$$

$$R_{2,3} = 61 \frac{\Omega}{sq} \left( \frac{360 \Omega}{60.125 \Omega} \right) = 365.2 \Omega (2) = 730.5 \Omega \quad (13)$$

### D. Testing Setup

The electrical circuit that is created by this resistor design is shown in figure 3.

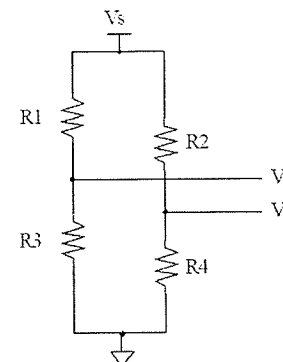


Fig. 3. Wheatstone Bridge Circuit for Sensing Changes in Pressure [1]

If there is no force on the circuit,  $V^+$  and  $V^-$  should be the same voltage because there will be no strain on the diaphragm and therefore no change in the resistance of any resistor. Likewise, if there is a force induced on the diaphragm,  $V^-$  will not be equal to  $V^+$ . Using a voltage divider equation,  $V^+$  and  $V^-$  can be found using (14), (15).

$$V^+ = V_s \left( \frac{R_3}{R_3 + R_1} \right) \quad (14)$$

$$V^- = V_s \left( \frac{R_4}{R_2 + R_4} \right) \quad (15)$$

$$V_{out} = V^+ - V^- \quad (16)$$

Without a pressure on the diaphragm,  $V^+$  and  $V^-$  are both equal to  $V_s/2$  and therefore  $V_{out}=0$ . With applied force it can be found using (14)-(16). It is also important to note that a symmetrical design is important because unequal strain could be placed on resistors giving false data.

### III. FABRICATION

Starting from a thickness of 500 microns, Silicon wafers were polished down to 300 microns to obtain the proper diaphragm thickness. The polishing will be done using a Strassbaugh CMP tool. A CMP clean and an RCA clean was performed to remove contaminants off of the wafer. 1500 angstroms of silicon-nitride was deposited on both sides of the wafer.

The first lithography step is done at the backside of the wafer. The resist was applied onto the wafers using the SVG Wafer Track.

The resist was then exposed using a Karl Suss MA150 Contact Aligner. The resist was hand-developed for in CD-26 developer. A plasma etches the nitride away and the resist was removed by oxygen plasma. The leftover nitride on the backside was used as hardmask, and on the frontside was used to protect silicon from KOH solution.

The diaphragm was formed by the KOH etching the Silicon at 54.7 degree angles long enough to only leave a 25 micron diaphragm. Polysilicon was deposited on the frontside of the wafer using an LPCVD and was doped using phosphorus Spin-On-Glass (SOG). Liquid glass N250 was spin coated onto the frontside of the wafer and a drive-in was performed.

The second lithography step defines the poly resistors. A manual resist coat was then necessary because the holes etched in the back of the wafer cannot be held down by vacuum in the wafer track.

In order to align mask level 1 to the back of the wafer, a drop of water was placed on the wafer and placed on the first mask. An optical microscope was used to align to the second mask level by features on the edge of the mask.

The resist was stripped and of 10000Å of aluminum was sputtered onto the wafer using CVC 601. The aluminum then is patterned with the third mask and then etched. [1]

### IV. TESTING AND RESULTS

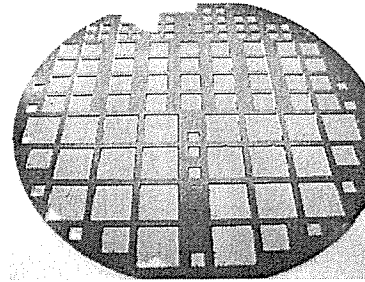


Fig. 4. Backside diaphragms after 3 hour KOH etch

Figure 4 shows the backside of the silicon wafer after a 3 hour KOH etch. The etch was supposed to last 4 hours but were taken out early because the ProTEK that was used to protect the front side was becoming etched. This resulted in slightly thicker (~120µm) diaphragms.

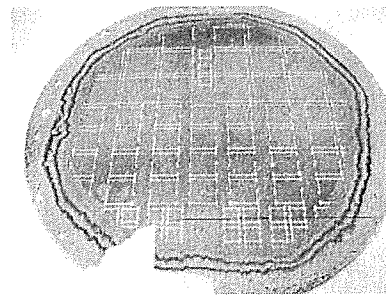


Fig. 5. Front of wafer after 3 hour KOH etch

Due to the ProTEK etching in the KOH the edges were no longer protected. Figure 5 shows that ProTEK was thinner on the sides and therefore became etched first.

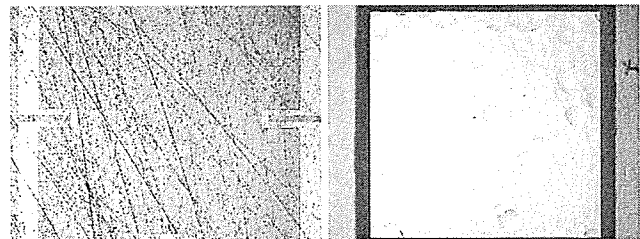


Fig. 6 a. Micrograph of top of sensor b. Micrograph of the diaphragm

Figure 6 shows the top and back view of a 9mm² device taken with an optical microscope.

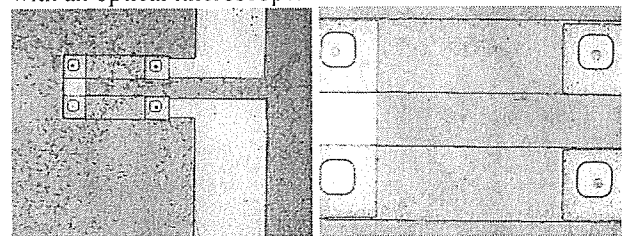


Fig. 7 Micrographs a poly resistor

Figure 7 shows pictures of the poly resistors. They do not indicate any device degrading process flaws, however the electrical testing resulted in open circuits. SEM images are needed to further investigate the cause of this issue.

## V. CONCLUSION

A MEMS piezoresistive multi-sensor was designed and fabricated in the Semiconductor Manufacturing and Fabrication Laboratory at the Rochester Institute of Technology. The electrical testing resulted in open circuits most likely due to poor Aluminum step coverage. SEM images should be taken to properly investigate the problem.

## REFERENCES

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