Bulk Micromachined Pressure Sensor

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Abstract- **Bulk micromachined piezoresistive pressure sensor was designed, fabricated, packaged, and tested at RIT laboratory facility. Every aspect of the fabrication is studied thoroughly and used as an educational tool in better understanding the fabrication of MEMs devices.**

***Index Terms*— Bulk Micromachined, MEMS, Pressure Sensor, Fabrication**

I. INTRODUCTION

Pressure sensors have a wide-range of applications in various fields, from automotive industry to medical equipments, such as airbag system and respiratory devices. A typical piezoresistive pressure sensor consists of two main components: a diaphragm and resistors. They are two methods of fabricating these parts: bulk (BM) and surface (SM) micromachined. In the later one, the diaphragm is built on top of the substrate surface. It offers several advantages in comparison to BM pressure sensor: smaller size, better dimensional control, and compatibility to CMOS technology. BM pressure sensor, on the other hand, utilizes the substrate as the diaphragm. There are also some advantages to this method: better mechanical properties and well-developed technology. [1]

As part of the project for MEMs course at RIT, students are to design and fabricate bulk micromachined piezoresistive pressure sensor. Each student was given a design space of 5000 µm by 5000 µm. The mask layout was designed using Mentor Graphics layout software package. Arrays of pressure sensors of different designs were fabricated as a class project.

II. DESIGN AND ANALYSIS

The design utilizes a thin square diaphragm made by etching a hole at the backside of a Si-substrate to almost all the way through the front surface, leaving only 20-30 µm thin layer of silicon. Polysilicon resistors are built on top of the diaphragm. Any deflection due to pressure differences on the two sides of the diaphragm will induced either compressive or tensile stress on the resistors, changing slightly their resistances. Thus, there is a direct relation between the change in resistor values and pressure applied to the diaphragm. Figure 1 shows the cross-sectional and top view of the pressure sensor. There are several aspects to consider in this design:

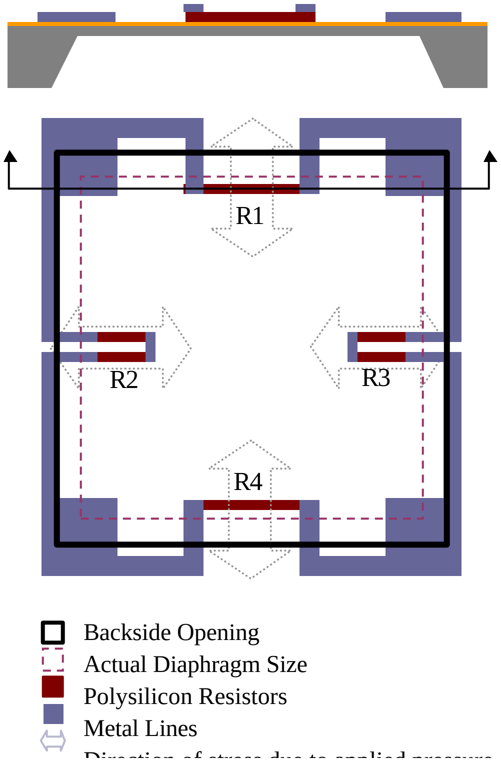

Fig. 1. Piezoresistive Pressure Sensor

A. *Diaphragm Size*

This includes the area and thickness of the diaphragm. Since directional KOH etch is used, the mask-defined backside opening will be larger than the actual diaphragm size. The actual diaphragm size can be calculated using the following formula.

$$L_{actual} = L_{mask} - 2\left(\frac{t_{sub} - t_{dia}}{\tan 54.7^{o}}\right) \qquad (1)$$

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where L_{mask} and L_{actual} are the mask-defined and actual length of square diaphragm, respectively. The t_{sub} and t_{dia} are the substrate and diaphragm thickness, respectively. KOH etches along (111) plane; thus, it makes 54.7^{o} angle with respect to (100) Si-substrate (see Figure 1).

Moreover, the combination between the size and thickness of the diaphragm determine the pressure range and sensitivity. The larger the diaphragm, the lower is the pressure range and vice versa. The thicker the diaphragm, the higher is the pressure range and vice versa. Improper design can either damage the diaphragm because of over stress or result in small signal detection because the diaphragm is too rigid.

B. *The Placement of the Polysilicon Resistors*

The placement of polysilicon resistor on top of the diaphragm is very crucial. In order to obtain an optimized design, these resistors have to be placed on where the stress on the diaphragm is the highest when pressure is applied. The stress on a square diaphragm is directly proportional to the applied pressure and given as follows. [2]

$$s = (0.3)\left(\frac{L}{H}\right)^2 .P \qquad (2)$$

where σ is the stress, L and H are the length and thickness of the diaphragm, and P is the applied pressure. Knowing the stress, strain can be calculated. Strain gives information how the dimensions of the polysilicon resistors change with applied stress.

$$\in = \frac{s}{E} = \frac{\Delta L}{L} = \frac{\Delta W}{W} \qquad (3)$$

where $\in$ is the strain, E is the Modulus Young. ΔL and L are the change in length and initial length, respectively. For polysilicon, $E = 1.9 \text{ x } 10^{11}$ N/m^2.

In a square diaphragm, the center of the diaphragm is the pressure center. The stress is distributed radially outward from the center and it is illustrated as the dashed circle in Figure 2. The maximum stress will occur at the four points where the dashed circle intercepts with the edge of the diaphragm. Thus, poly piezoresistors will be placed as close as possible to these points.

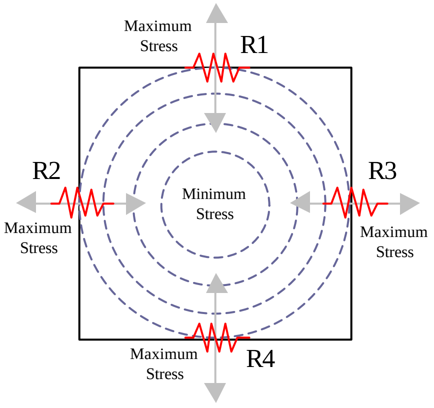


Fig. 2. Stress distribution on a square diaphragm.

C. *Symmetric Design*

When pressure is applied to the diaphragm, R1 & R4 become wider, reducing their total resistance, and R2 & R3 become longer, increasing their total resistance. The change in length or width can be obtained based on equation (2) and (3). The resistance can be calculated as follows.

$$R1, R4 = R_S .\frac{L}{W + \Delta W} = R_S .\frac{L}{W + \in .W} \qquad (4)$$

$$R2, R3 = R_S .\frac{L + \Delta L}{W} = R_S .\frac{L + \in .L}{W} \qquad (5)$$

Where R_S is the polysilicon sheet resistance. L and W are the actual length and width of the resistors. ΔL and ΔW are the change in length and width due to applied pressure. This behavior can be exploited to double the effect of pressure on output signal by connecting them as shown in Figure 3.

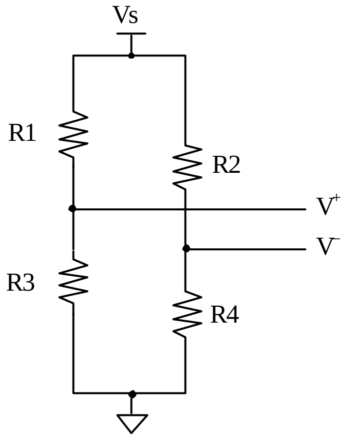


Fig. 3. Voltage divider in parallel enhanced the output signal to the applied pressure.

The configuration is no other than two voltage dividers connected in parallel. The output signals can be expressed as follows.

$$V^+ = \left(\frac{R3}{R1 + R3}\right) V_S \qquad (6)$$

$$V^- = \left(\frac{R4}{R2 + R4}\right) V_S \qquad (7)$$

$$V_{out} = V^+ - V^- \qquad (8)$$

Without any pressure, R1 to R4 have the same resistor value. Thus, V+ and V- have the same value that is Vs/2; thus, V_{out} is zero. When the pressure is applied, V^+ will be slightly larger than Vs/2, and V^- will be slightly less than Vs/2, resulting in non-zero V_{out}. It is expected that as the applied pressure increases, V_{out} will increase also. Symmetric design is needed to obtain an accurate relationship between V_{out} with the applied pressure.

II DESIGN EXAMPLE

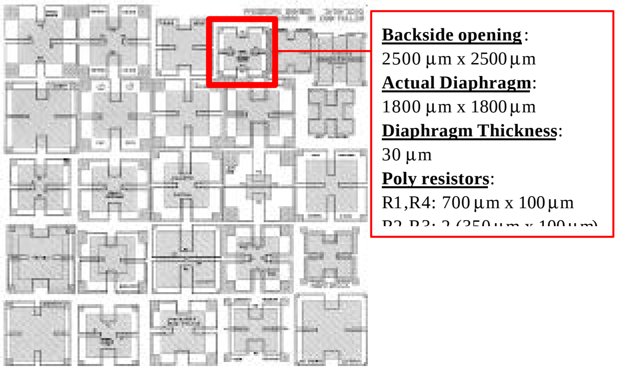
Lets look closely on one particular sensor design. The backside opening was designed to be 2500 µm by 2500 µm. The desired diaphragm thickness is 30 Å. According to equation (1), the actual diaphragm is 1800 µm by 1800 µm.

Poly resistors are built on top of the diaphragm. R1 and R4 have dimension of L = 700 µm and W = 100 µm. For R2 and R3, each consists of two resistors L= 350 µm and W = 100 µm in series. Based on the actual measurement in the lab, Rs of the doped polysilicon is 60.7 Ω/sq. Theoretically, R1 to R4 should have the same resistor value of 424.9 Ω when there is no pressure applied. Assuming that V_S is 5 volts, both V+ and V– will be exactly 2.5 volts. V_{out} should be zero.

Pressure of 14.7 psi or 103 kN/m^2 is then applied to the diaphragm. The diaphragm deflects. Based on equation (2), the calculated stress (σ) is 1.11×10^8 N/m^2. The strain is then calculated using equation (3), $\in = 5.85 \times 10^{-4}$. Using this value in conjunction with equation (4) & (5), the resistors values are calculated. R1 & R4 become 424.653 Ω, and R2 & R3 become 425.149 Ω. This results in V^+ of 2.5014 volts and V^- of 2.4986 volts, resulting in V_{out} of 2.8 mV.

III. FABRICATION

The mask was fabricated using MEBES III E-beam maskmaking system. Figure 4 shows the array of different BM pressure sensor designs.



Backside opening:
2500 µm x 2500 µm
Actual Diaphragm:
1800 µm x 1800 µm
Diaphragm Thickness:
30 µm
Poly resistors:
R1,R4: 700 µm x 100 µm
R2,R3: 2 (350 µm x 100 µm)

Fig. 4. Mask of Arrays of BM Pressure Sensor

Since lithography will be performed on both sides of the wafer, the backside surface had to be polished. The polishing was done using Strassbaugh CMP tool with the following process parameters:

- Slurry: Lavisil-50-054, drip rate: ~1 drop/sec.
- Down Pressure = 8 psi
- Quill Speed = 70 rpm
- Oscillation Speed = 6 per min
- Table Speed = 50 rpm (~10 Hz)
- Polish time = 15 min./wafer

To remove any dust particles and contaminants on the wafer surface, standard RCA clean was performed.

A thin silicon-nitride, about 1500 Å, was deposited using LPCVD method. The complete process parameters is given as follows.

- Temperature = 800°C
- Pressure = 375 mTorr
- Dichlorosilane (SiH_2Cl_2), flow = 60 sccm
- Ammonia (NH3), flow = 150 sccm
- Rate = 60 Å/min +/- 10 Å/min
- Deposition time ~25 min

This nitride layer was deposited on both sides of the wafer.

The first lithography step was done at the backside of the wafer. The resist was applied onto the wafers using SVG WaferTrack with the following process recipe:

- Dehydration Bake at 200°C for 2 min.
- HMDS Vapor Prime at 140°C for 1 min.
- Spincoat Shipley 812 at 4500 rpm for 1 min.
- Softbake at 90°C for 1 min.

The resist then was exposed using SUS MA150 Contact Aligner for 10 sec, giving exposure dose of 50 mJ/cm^2. The resist then was hand-developed for 60 sec in CD-26 developer.

The next step was to etch the nitride on the specified regions where are not protected with photoresist. This was done using LAM 490 AutoEtch. The standard recipe was used:

- SF6 flow = 30 sccm, He flow = 150 sccm
- Pressure= 340 mTorr
- Power = 175 watts
- Endpoint detection with 20% overetch.

After the nitride etch, resist was removed using oxygen plasma on the Branson Asher. The leftover nitride on the backside was used as hardmask, and on the frontside was used to protect silicon from KOH solution.

The diaphragm then was formed by etching the silicon from the backside opening to almost all the way to the front surface, leaving 30 µm thin of silicon layer. This was done using KOH Etch apparatus. The etch depth was monitored using focus dial on the microscope that is quite accurate down to 1 µm resolution. The etch rate was 0.877 µm/min.

The next step was to deposit polysilicon on the frontside of the wafer using LPCVD. The target thickness was 6000 Å. The following list contains the process detail:

- Temperature = 610 °C
- Pressure = 330 mTorr
- Silane (SiH_4) flow 45%
- Deposition Rate = 100 Å/min.
- Deposition time = 60 min.

The polysilicon then was doped using phosphorus Spin-On-Glass (SOG). Liquid glass N250 was spin coated onto the frontside of the wafer. The phosphorus was driven into the polysilicon using thermal process. Upon completion, the resistivity of the poly layer was measured using 4-point-probe, Rs = 60.7 Ω/sq.

The second lithography step was done to define the shape of the poly resistors. The resist coating was done manually because the vacuum system on the SVG track could not work on the holes at the backside of the wafer. Another challenge in this particular step was alignment. The following approach was used. Mask level 1 was aligned to the backside of the wafer. The wafer was taped onto the mask. The mask level 1 was then aligned to mask level 2 through some features outside wafer perimeter. The mask level 2 then was taped onto mask level 1 (see Figure 5).

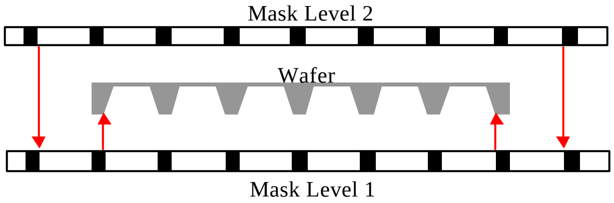


Fig. 5. Frontside to Backside Alignment.

After creating the poly resistors, the resist then was striped. A blanket of 7500Å thick of Aluminum was sputtered onto the wafer using CVC 601. The following process parameters were used.

- Power = 2000 watts
- 5 mTorr Argon
- Sputter Time = 30 min

The aluminum then was patterned with the third mask. The standard lithography procedure was applied. Unwanted aluminum was etched using Al-etchant that was heated to 50°C. The resist was stripped, and the wafers was sintered at 450°C in N_2/H_2 for 20 min. Sintering makes better Al/poly contact by consuming native oxide at the interface.

The wafer then was tested using probe station for functionality. For an extensive characterization, the pressure sensor needed to be packaged individually and tested. The wafer was diced, and mounted on a carrier that has holes on the middle using epoxy glue. The chip then was connected to copper pads at the four corners using Orthodyne wire bonder.

Fig. 6. Packaging

Furthermore, this system than was connected to the compressed gas pressure regulator. By doing so, pressure applied to the diaphragm can be regulated. Thus, a relationship between applied pressure and output signal can be obtained.

IV. TESTING & RESULTS

The following SEM picture was used to estimate the diaphragm thickness. It was approximated to be 30 μm.

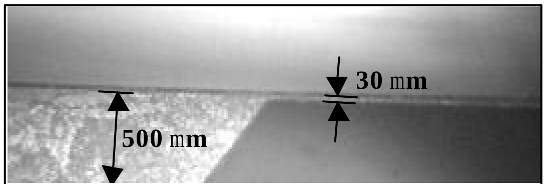


Fig. 7. SEM cross section of the diaphragm

Using the manual probe station, a particular pressure sensor on Figure 4 was tested. The supply voltage was set to 5 volts. Table 1 shows the comparison between the theoretical values and actual measurement.

Parameters	Theoretical	Actual
V+ no vac (V)	2.5	2.66
V– no vac (V)	2.5	2.62
V_{out} no vac (mV)	0	33.20
R1 & R4 no vac (Ω)	424.9	–
R2 & R3 no vac (Ω)	424.9	–
V+ vac (V)	2.5014	–
V– vac (V)	2.4986	–
V_{out} vac (mV)	2.8	36.85
R1 & R4 (Ω) vac	424.652	–
R2 & R3 (Ω) vac	425.149	–
V_{out}(vac) – V_{out}(no vac)	**2.8 mV**	**3.65 mV**

Table 1. Results

The design was not quite symmetric. This can be caused by improper alignment, non-uniform doping and/or overetching of polysilicon. However, the device worked in the voltage range as predicted by the theory. In fact, the device showed a larger output signal than predicted.

V. CONCLUSIONS

Bulk micromachined piezoresistive pressure sensors were designed. Calculations for expected output voltage were made. Masks were made. A fabrication process was designed. Devices were fabricated. Devices were tested at the wafer level. Wafers were diced and chips packaged for testing. Reasons for some device failures were identified. Test results agreed with predictions. In conclusion, the laboratory project was successful in providing a platform for the students to learn different aspects involved in designing MEMs devices[3]

REFERENCES

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