Lecture - 37
Pressure Sensor Design concepts, Processing, and Packaging

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Topics

- Concepts and types of Pressure sensors
- Definitions and Design criteria
- Single crystal Piezoresitive pressure sensor
- Pressure sensor Packaging
Pressure sensor Concepts

Sensor element

Membrane (silicon)
Membrane (Spring)

Single crystal Silicon membrane

Creep, Fatigue and Hysteresis are virtually absent

compared to metal membrane
Sensing Element

- Piezoelectric
- Capacitive
- Piezoresistive
Piezoelectric sensing

Piezoelectric crystal (Quartz, PZT) gives electrical output when subjected to stress

**Merits:** External power supply not required

**Disadvantages:**

- Silicon is not piezoelectric. Necessary to externally glue a piezoelectric pellet on membrane: Not suitable in IC technology
- Not suitable for static pressure sensing due to charge leakage.
Capacitive Pressure sensor

Detects the deflection of membrane as a variation in capacitance between two plates

**Merits:**

- High sensitivity.
- Absence of Temperature coefficient of sensitivity

**Disadvantages:**

- Electronics for capacitance to voltage conversion
- CV is not linear. Force balancing by electronics
Piezoresistive Sensors

They make use of the change in R due to the change in their physical dimensions and carrier mobility when subjected to strain.

**Merits:**

- Simple to fabricate
- No need of electronics
- Linear characteristics over wide range of Pressures

**Disadvantages:**

- Temperature coefficient of resistivity and Sensitivity

\[
V_0 = \frac{\Delta R}{R} V_{in}
\]
Silicon micromachined pressure sensor

P-type implanted resistors, R1, R2

Fluid Pressure - P

Need backside alignment

Top View of resistor and metal interconnection

\[ R_1 = R_2 = R_3 = R_4 = \frac{\Delta R}{R} \]

\[ V_0 = V_{in} \frac{\Delta R}{R} \]
Longitudinal stress $\sigma_1$ along dotted line

P=3 Bar

Membrane thickness h=10$\mu$m

$1 \text{N/mm}^2 = 1 \text{ MPa} = 10 \text{ Bar}$

1 Bar = 760 Torr = 760 mm Hg

$1N/mm^2 = 1 \text{ MPa} = 10 \text{ Bar}$

$1 \text{ Bar} = 760 \text{ Torr} = 760 \text{ mm Hg}$
PIEZORESISTIVE EFFECT

Strain on the crystal structure deforms energy band structure, and this changes resistivity due to change in the mobility.

Gauge Factor \( G = \frac{\Delta R}{R} \frac{1}{\varepsilon} \) where \( \varepsilon = \text{strain} = \frac{\Delta L}{L} \)

\[
R = \frac{\rho L}{A}.
\]

\[
\Delta R = \frac{\rho}{A} \Delta L + \frac{L}{A} \Delta \rho - \rho L \frac{\Delta A}{A^2}
\]

\[
\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L} - \frac{\Delta A}{A} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L} - \frac{2\Delta D}{D} \quad \text{(1)}
\]

\[
\frac{\Delta A}{A} = \frac{2\Delta D}{D}
\]

‘D’ is diameter.

\[
\frac{\Delta D}{D} = -\nu \frac{\Delta L}{L} = -\nu \varepsilon \quad \text{(2)}
\]

\( \nu \) is Poisson's ratio

\[
G = \frac{\Delta R}{\varepsilon R} = \frac{\Delta \rho}{\varepsilon \rho} + (1 + 2\nu)
\]
## COMPARISON OF GAUGE FACTORS

<table>
<thead>
<tr>
<th>TYPE OF STRAIN GAUGE</th>
<th>GAUGE FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal foil</td>
<td>1 to 5</td>
</tr>
<tr>
<td>Thin-film metal</td>
<td>≈2</td>
</tr>
<tr>
<td>Diffused semiconductor</td>
<td>80 to 200</td>
</tr>
<tr>
<td>Poly crystalline silicon</td>
<td>≈30</td>
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</tbody>
</table>
Piezoresistive coefficient

Resistance change can be calculated as a function of the stress $\sigma$ using the concept of piezoresistive coefficient $\pi$

$$\frac{\Delta R}{R} = \pi \sigma = G \varepsilon$$

Gaugefactor, $G = \pi \frac{\sigma}{\varepsilon} = \pi E$

‘E’ is Young’s modulus =190 GPa for Silicon
Effect of Longitudinal stress $\sigma_L$ and transverse stress $\sigma_T$ on R

Uniform Pressure ‘P’ is applied on Diaphragm (directed towards the plane Of the paper)

The stress components on the membrane at $x = a$ are

$$\sigma_x = P \frac{a^2}{h^2}, \quad \sigma_y = \nu P \frac{a^2}{h^2}$$

$\nu$ is Poisson ratio = 0.3 for Si

On the Resistor R, $\sigma_L = \sigma_x$ ; $\sigma_T = \sigma_y$
On the Resistor $R$,

\[ \sigma_L = \sigma_x = P \frac{a^2}{h^2} \]
\[ \sigma_T = \sigma_y = \nu P \frac{a^2}{h^2} \]

\[ \frac{\Delta R}{R} = \pi L \sigma_L + \pi T \sigma_T \]
\[ \frac{\Delta R}{R} = \pi L \left( P \frac{a^2}{h^2} \right) + \pi T \left( \nu P \frac{a^2}{h^2} \right) \]

$\pi_T = -\pi_L$ along $<110>$ direction for single crystal Si

\[ \frac{\Delta R}{R} = \pi_l P \frac{a^2}{h^2} \left( 1 - \nu \right) \]
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\[ \frac{\Delta R}{R} = \pi_l P \frac{a^2}{h^2} (1 - \nu) \]

Use the \( \pi_L \) of the resistor material

Corresponding strain = \( \varepsilon = \frac{\text{Stress}}{E} = \frac{P a^2}{h^2} (1 - \nu) \)

In terms of strain we can express for single crystal p-type resistor

\[ \frac{\Delta R}{R} = G_L \varepsilon = \frac{G_L}{E} P \left( \frac{a}{h} \right)^2 (1 - \nu) \]

\( G_L = 100 - 120 \) for single crystal silicon
Single crystal Piezoresistive Pressure sensor

Pressure $P$ ↓ ↓ ↓ ↓ ↓

p-type resistor

n-Si

$V_0 = \frac{\Delta R}{R} V_{in} = P \frac{a^2}{h^2} (1 - \nu) \pi L V_{in}$

$R_1 = R_2 = R_3 = R_4 = R$
Sensitivity and Burst Pressure

\[ V_0 = \frac{\Delta R}{R} V_{in} = P \frac{a^2}{h^2} (1 - \nu) \pi L V_{in} \]

Sensitivity, \[ S = \frac{\Delta V_0}{\Delta P} \frac{1}{V_{in}} = \pi L \frac{a^2}{h^2} (1 - \nu) \]

Burst Pressure, \( P \) is the \( P_{max} \) at which the maximum stress \( \sigma_{max} \) on the membrane is the critical stress = yield strength

\[ \sigma_{max} = P_{max} \left( \frac{a}{h} \right)^2 \]

\[ \sigma_{max} = \sigma_{critical} = P_{burst} \left( \frac{a}{h} \right)^2 = 7 \text{ GPa} \text{ for Si} \]

1 atmosphere=1bar = 10^5 Pa ; 1 GPa = 10^4 bar
Upper limit on sensitivity

Sensitivity is higher when membrane is thinner (lower values of $h$).

**Note:** when $a/h=25$, $w_0/h=0.1$, $P=2.2$ bar

For a given ‘$a$’, the Lower limit on ‘$h$’ is decided by:

(a) Burst pressure which should be about FIVE times the maximum operating pressure.

(b) Nonlinearity of the sensor due to stretching when maximum deflection $w_0$ is comparable to thickness.

$$P = E \frac{h^4}{a^4} \left[ g_1 \frac{w_0}{h} + g_2 \left( \frac{w_0}{h} \right)^3 \right]$$

- $g_1 = \frac{4.13}{1-\nu^2} = 4.54$
- $g_2 = \frac{1.98(1-0.585\nu)}{1-\nu} = 2.33$

Second term is due to “Ballooning Effect”. First (linear) term is due to Bending.
Pressure Sensor Types

• **Absolute Pressure sensors** - measure relative to Vacuum (atmospheric pressure measurement)

• **Gauge Pressure Sensors** – Measure relative to atmospheric Pressure - Examples are (1) blood pressure measurement, (2) Vacuum sensors gauge sensors designed to operate in the negative pressure region)

• **Differential Pressure Sensors** - Measure difference between two pressure measurands (Example of application is High Pressure Oxidation System)
**Piezoresistive pressure sensor**

**Process:**
1. Anisotropic etching of top Silicon wafer to realize the thin Membrane
2. Implanting for Boron in the regions where the resistors need to be located on the top wafer.
3. Interconnect the four resistors to form Wheatstones Bridge
4. Bond a bottom wafer with a hole to act as the pressure port
Lithography

1. Grow 1μm Thick SiO₂

SiO₂

(100) Si

230 μm

SiO₂

SiO₂

2. Spin PPR at 4000RPM and pre-bake in an oven at 90 - 100°C for 20 - 30 minutes to drive away the solvents

PPR

SiO₂

(100) Si

230 μm

SiO₂

SiO₂

3. Expose to collimated UV (300-430nm) or deep UV (150-300nm) through a mask

Photo-mask

PPR

SiO₂

(100) Si

230 μm

SiO₂

SiO₂

4. Dip in a developer to dissolve PPR from the exposed regions

PPR

SiO₂

(100) Si

230 μm

SiO₂

SiO₂
6. Post bake 1t 120°C for 20-30 min

7. Etch the oxide in the window region, protecting the back side oxide using aler of PPR or wax

8. Strip off the PPR by dipping in acetone
KOH etching to realize a 14 μm Diaphragm

Use 40 percent KOH at 80°C and immerse the wafer into this solution. The etch rate for this solution is 1 μm / min. The solution must be stirred constantly either using a magnetic stirrer or by bubbling nitrogen through it.

Etch the oxide fully in BHF and then clean by immersing the wafer into a 1:3 mixture of H₂O₂ and H₂SO₄ (Piranha Solution) for 15 minutes.

Flip the wafer vertically to have the diaphragm on the top.
Top view of the wafer

We can not see the location of the diaphragm looking from the top

Cross section
IR or backside alignment to position the resistor mask.
IR light or backside alignment to position the resistor mask
Photograph showing the close up view of the alignment of the resistor and metal pattern with respect to the diaphragm structure
Photograph showing the Back side etching and the V- groove side of a rectangular diaphragm cavity
Basic Packaging Scheme for Pressure sensor
Basic First order Pressure sensor Packaging