Evaluation of Pressure Sensor Performance

Dr. Lynn Fuller

Webpage: http://people.rit.edu/lffeee

Microelectronic Engineering
Rochester Institute of Technology
82 Lomb Memorial Drive
Rochester, NY 14623-5604
Tel (585) 475-2035
Fax (585) 475-5041
Email: Lynn.Fuller@rit.edu

Department webpage: http://www.microe.rit.edu

3-17-2011 Pressure_Sensor_Lab.ppt
Introduction
Theory
SEM Pictures
Basics
Response
Offset, Span, Linearity, etc.
Compensation
Temperature Dependence and Compensation
Frequency Response
References

Thickness = 10 μm
Diameter 75 mm
INTRODUCTION

In this lab we will test piezoresistive pressure sensors made at RIT and compare them with sensors made by Freescale Semiconductor.
FREESCALE MPX2202 SERIES PRESSURE SENSORS

UNIBODY PACKAGES

MPX2202A
CASE 344-15

MPX2202AP/GP
CASE 344B-01

MPX2202DP
CASE 344C-01

MPX2202ASX
CASE 344F-01

SMALL OUTLINE PACKAGES

MPXV2202GP
CASE 1351-01

MPXV2202GP
CASE 1369-01

MPXM2202A
CASE 1320-02

MPXV2202GS/AS
CASE 1320A-02
RIT PRESSURE SENSORS
The equation for stress at the center edge of a square diaphragm (S.K. Clark and K. Wise, 1979):

\[
\text{Stress} = 0.3 \, P (L/H)^2
\]

where P is pressure, L is length of diaphragm edge, H is diaphragm thickness.

For a 3000μm opening on the back of the wafer the diaphragm edge length L is:

\[
L = 3000 - 2 \left( \frac{500}{\tan 54.74^\circ} \right) = 2290 \, \mu m
\]
Stress = 0.3 P (L/H)^2

If we apply vacuum to the back of the wafer that is equivalent to and applied pressure of 14.7 psi or 103 N/m^2
P = 103 N/m^2
L= 2290 µm
H= 25 µm
Stress = 2.49E8 N/m^2

Hooke’s Law: Stress = E Strain  where E is Young’s Modulus
σ = E ε

Young’s Modulus of silicon is 1.9E11 N/m^2
Thus the strain = 1.31E-3 or .131%
CALCULATION OF EXPECTED OUTPUT VOLTAGE (Cont.)

The sheet resistance (Rhos) from 4 point probe is 61 ohms/sq
The resistance is \( R = \text{Rhos} \frac{L}{W} \)
For a resistor \( R_3 \) of \( L=350 \, \mu m \) and \( W=50 \, \mu m \) we find:
\[
R_3 = 61 \left( \frac{350}{50} \right) = 427.0 \, \text{ohms}
\]

\( R_3 \) and \( R_2 \) decrease as \( W \) increases due to the strain
Assume \( L \) is does not change, \( W' \) becomes \( 50+50 \times 0.131\% \)
\[
W' = 50.0655 \, \mu m
\]
\[
R_3' = \text{Rhos} \frac{L}{W'} = 61 \left( \frac{350}{50.0655} \right) = 426.4 \, \text{ohms}
\]

\( R_1 \) and \( R_4 \) increase as \( L \) increases due to the strain
Assume \( W \) does not change, \( L' \) becomes \( 350 + 350 \times 0.131\% \)
\[
R_1' = \text{Rhos} \frac{L'}{W} = 61 \left( \frac{350.459}{50} \right) = 427.6 \, \text{ohms}
\]
CALCULATION OF EXPECTED OUTPUT VOLTAGE (Cont.)

No stress
Vo2 - Vo1 = 0

With stress
Vo2 - Vo1 = 0.007V = 7 mV
In addition to the effects of strain on the resistance if the resistor is made of single crystal silicon there is also a significant piezoresistive effect on the resistor value. Strain effects the mobility of holes and electrons in silicon. The resistors on the diaphragm of the pressure sensor drawn above have current flow longitudinal (R1 and R4) and transverse (R2 and R3) to the strain. The strain is tensile on the top surface of the diaphragm where the resistors are located if positive pressure is applied to the top of the diaphragm. The piezoresistive coefficient for R1 and R4 is 71.8 and for R2 and R3 is -66.3 E-11/Pa. The calculations above give the stress as 2.49E8 Pa thus the hole mobility will decrease in R1 and R4 (R increases in value) by 2.49E8 x 71.8e-11 = 17.9% while R2 and R3 (decrease in value) because the mobility increases by 2.49E8 x 66.3E-11 = 16.5%, thus the overall effect will be dominated by the piezoresistance rather than the effect of strain on the dimensions.
**EXPRESSION FOR RESISTANCE**

\[ R = R_0 \left[ 1 + \pi_L \sigma_{xx} + \pi_T (\sigma_{yy} + \sigma_{zz}) \right] \]

where \( R_0 = \frac{L}{W} \left( \frac{1}{q \mu (N, T) \text{ Dose}} \right) \)

\( \pi_L \) is longitudinal piezoresistive coefficient
\( \pi_T \) is transverse piezoresistive coefficient
\( \sigma_{xx} \) is the x directed stress, same direction as current
\( \sigma_{yy} \) is the y directed stress, transverse to current flow
\( \sigma_{zz} \) is the z directed stress, transverse to current flow

In the <110> direction

<table>
<thead>
<tr>
<th></th>
<th>( \pi_L (\text{E}^{-11}/\text{Pa}) )</th>
<th>( \pi_T (\text{E}^{-11}/\text{Pa}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>-31.6</td>
<td>-17.6</td>
</tr>
<tr>
<td>holes</td>
<td>71.8</td>
<td>-66.3</td>
</tr>
</tbody>
</table>

(100) wafer
<110> directions
CALCULATION OF EXPECTED OUTPUT VOLTAGE FOR SINGLE CRYSTAL RESISTORS

No stress
Vo2 - Vo1 = 0

With stress
Vo2 - Vo1 = 0.854V
= 854 mV
SEM OF RIT PRESSURE SENSOR

Front

Back

Rochester Institute of Technology
Microelectronic Engineering
5 Volts

Vo2 = 2.5035v

Vo1 = 2.4965v

Check that Vo1 and Vo2 are near Vsupply/2 and Vo ~ 0

Apply and release chuck vacuum to observe change in output voltage
PRESSURE SENSOR PACKAGING
Apply pressure, measure and compare with other pressure gages. Collect data.
OUTPUT VOLTAGE VERSUS PRESSURE

MEMS Pressure Sensor Output
Polysilicon Resistors

\[
y = 0.0002x^2 + 0.586x + 60.593
\]

<table>
<thead>
<tr>
<th>psi</th>
<th>mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60.6</td>
</tr>
<tr>
<td>5</td>
<td>63.84</td>
</tr>
<tr>
<td>10</td>
<td>66.32</td>
</tr>
<tr>
<td>15</td>
<td>68.95</td>
</tr>
<tr>
<td>20</td>
<td>72.28</td>
</tr>
<tr>
<td>25</td>
<td>75.62</td>
</tr>
<tr>
<td>30</td>
<td>78.68</td>
</tr>
<tr>
<td>35</td>
<td>81.25</td>
</tr>
<tr>
<td>40</td>
<td>84.39</td>
</tr>
<tr>
<td>45</td>
<td>87.21</td>
</tr>
</tbody>
</table>

Rochester Institute of Technology
Microelectronic Engineering

© March 17, 2011  Dr. Lynn Fuller
Pressure Sensor

Temperature Sensor

Humidity Sensor

Diffused Resistors
Length =
Width =

Note: upper left is not connected so individual resistances can be measured.
**ELECTRICAL MEASUREMENTS**

Measured resistance:  
- \( R_{\text{top}} = 3.538 \, \text{Kohm} \)
- \( R_{\text{right}} = 3.537 \, \text{Kohm} \)
- \( R_{\text{bottom}} = 3.537 \, \text{Kohm} \)
- \( R_{\text{left}} = 3.537 \, \text{Kohm} \)

Measured Voltages:  
- \( V_{\text{o1}} = 2.535 \, \text{V} \)
- \( V_{\text{o2}} = 2.504 \, \text{V} \)
- \( V_{\text{o1}} - V_{\text{o2}} = 31.0 \, \text{mV} \)

\[ \text{Rhos} \approx 150 \, \text{ohm/sq} \]
**Output Voltage vs Pressure**

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Vo1-Vo2 (mV)</th>
<th>Pressure (psi)</th>
<th>Vo1-Vo2 @ 72°C (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30.9</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>1.49</td>
<td>34.2</td>
<td>1.33</td>
<td>28.3</td>
</tr>
<tr>
<td>2.09</td>
<td>35.4</td>
<td>3.3</td>
<td>31.9</td>
</tr>
<tr>
<td>3.19</td>
<td>37.6</td>
<td>5.55</td>
<td>36.1</td>
</tr>
<tr>
<td>4.12</td>
<td>39.4</td>
<td>6.6</td>
<td>38.1</td>
</tr>
<tr>
<td>5.42</td>
<td>42.1</td>
<td>9.95</td>
<td>44.6</td>
</tr>
<tr>
<td>6.43</td>
<td>45</td>
<td>11</td>
<td>46.8</td>
</tr>
<tr>
<td>7.11</td>
<td>45.8</td>
<td>13.12</td>
<td>51</td>
</tr>
<tr>
<td>8.2</td>
<td>47.9</td>
<td>14.45</td>
<td>55</td>
</tr>
<tr>
<td>9.27</td>
<td>50.1</td>
<td>15.77</td>
<td>56.8</td>
</tr>
<tr>
<td>10.16</td>
<td>51.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.21</td>
<td>53.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.16</td>
<td>55.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.2</td>
<td>57.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.05</td>
<td>59.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.24</td>
<td>62</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sensitivity = 0.406mV/psi/V
or 0.0589 mV/KPa/V
or 0.589 mV/KPa @ 10VDC
ZERO AND SPAN COMPENSATION

This spreadsheet can be used to find resistor values used to compensate a Wheatstone bridge resistor pressure sensor for output offset voltage and span. If we assume that the resistors are TaN thin film resistors that are adjusted by laser trimming then the trimmed value has to be higher than the nominal value. First adjust the value of Rzt and Rzb to set Vout trimmed to zero. Then set Rst and Rsb to make the trimmed stressed value equal to the specified output voltage at maximum applied pressure.

<table>
<thead>
<tr>
<th>Vsupply</th>
<th>Vout</th>
<th>Vo+</th>
<th>Vo-</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>%change</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 volts</td>
<td>5</td>
<td>5.012392</td>
<td>5.024722</td>
<td>5.015380988 volts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no trim</td>
<td>no trim</td>
<td>trimmed</td>
<td>trimmed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>nominal</td>
<td>stressed</td>
<td>stressed</td>
<td>stressed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>3637</td>
<td>3572.37</td>
<td>2.52487</td>
<td>2.54632</td>
<td>2.51701</td>
<td>2.6316642 volts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2</td>
<td>3637</td>
<td>3501.63</td>
<td>2.5</td>
<td>2.48415</td>
<td>2.51732</td>
<td>2.5066803 volts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3</td>
<td>3637</td>
<td>3501.63</td>
<td>24.8748</td>
<td>62.1642</td>
<td>-0.61917</td>
<td>25.003389 mV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4</td>
<td>3620</td>
<td>3565.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%change</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rzt</td>
<td>10000</td>
<td>10000 ohms</td>
<td>Vo+ = I_{total} * Rsb + I_{right} * R4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rst</td>
<td>250</td>
<td>1072 ohms</td>
<td>Vo- = I_{total} * Rsb + I_{left} * R2/Rzb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rzb</td>
<td>10000</td>
<td>11000 ohms</td>
<td>Vout = Vo+ - Vo-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rsb</td>
<td>250</td>
<td>1072 ohms</td>
<td>Vo+ = I_{total} * Rsb + I_{right} * R4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rsb</td>
<td>250</td>
<td>1072 ohms</td>
<td>Vo- = I_{total} * Rsb + I_{left} * R2/Rzb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rzt</td>
<td>10000</td>
<td>10000 ohms</td>
<td>Vout = Vo+ - Vo-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rochester Institute of Technology
Microelectronic Engineering
Bridge_Balance.xls
Diffused Resistors

Sensitivity $\sim = \frac{200 \text{mV}}{12 \text{psi}} = 10 \text{ mV/psi}$

Sensitivity $\sim = \frac{100 \text{mV}}{15 \text{psi}} = 6.67 \text{ mV/psi}$
EXCESSIVE PRESSURE
EVALUATION OVER TEMPERATURE

Polysilicon Resistors

Output Voltage vs. Pressure for Device 2

Zero-Span Compensated Pressure Sensor over Temperature

No Compensation

Compensated

Rochester Institute of Technology
Microelectronic Engineering
TEST SETUP FOR FREQUENCY MEASUREMENT
BALLOON ABOUT TO POP
MEASURED STEP RESPONSE

Data out of range

Period(1) not found  Vp-p(1) not found  Vavg(1) not found
Pressure Sensor

STEP TO IMPULSE TO FREQUENCY RESPONSE

Excel Spreadsheet

Data

Filtered
Normalized Step Response

Derivative gives Impulse Response

Fourier Transform Gives frequency response

Real Part in dB
This spreadsheet finds the frequency response from the measured step response. The measured step response is converted into a series of 128 data points. The derivative is found to get the impulse response. The Fourier transform of the impulse response is found to get the frequency response. The frequency response is the real part of the Fourier transform of the impulse response for positive frequencies.

Assume the step response (Rn) has the general form shown in the figure below, enter times to, tmid, tend

to = 0.002 sec, where Rn = 0
tmid = 0.004 sec, where Rn = 0.5
tend = 0.006 sec, where Rn = 1.0
MEASURED STEP RESPONSE

Measured Step Response from Oscilloscope

- 60 Hz noise
- filtered
FILTERED NORMALIZED STEP RESPONSE

Normalized Step Response versus time

Normalized Step Response
time (seconds)
IMPULSE RESPONSE

Impulse Response

time (seconds)

-5.00E+01 0.00E+00 5.00E+01 1.00E+02 1.50E+02 2.00E+02 2.50E+02 3.00E+02 3.50E+02 4.00E+02 4.50E+02

0 0.001 0.002 0.003 0.004 0.005 0.006 0.007 0.008 0.009

Rochester Institute of Technology
Microelectronic Engineering
FOURIER TRANSFORM

Real part of Fourier transform versus frequency

Frequency (Hz)

-1.00E+04 -8.00E+03 -6.00E+03 -4.00E+03 -2.00E+03 0.00E+00 2.00E+03 4.00E+03 6.00E+03 8.00E+03 1.00E+04

-45 -40 -35 -30 -25 -20 -15 -10 -5 0 5
REFERENCES

1. The example calculations shown on page 4-10 make a lot of assumptions about the fabrication process such as the starting wafer is 500um thick. In fact the starting wafer is thinned and polished to reduce the KOH etch time and the back grinding process is not that exact giving variation of starting wafer thickness between 250 and 350um. List other variables that might vary by more than 10% and discuss how that would effect the sensitivity and offset of the pressure sensor.

2. Discuss the linearity of the pressure sensor. Why do thicker diaphragms give more linear results over a given pressure range. How is the sensitivity affected by thicker diaphragms.

3. Should the pressure be applied to the top or bottom of the sensor? Why?

4. If the compensation network uses laser trimmed resistors which resistor should be trimmed to make the output zero if Vo+ is +50mV to begin with?

5. The bridge balance Excel spread sheet was made for poly resistor pressure sensors. Modify it to do either poly or diffused resistor pressure sensors.
Show MEMS chip
Take Picture
Apply Vacuum
Take Picture
Measure Vo1, Vo2 and Vo1-Vo2 with no pressure
Measure Vo1, Vo2 and Vo1-Vo2 with pressure
For RIT packaged device take data for Vo1-Vo2 versus Pressure
Determine Offset and span
Correct offset and span
Take data for Vo1-Vo2 with corrections.
Take data for Commercial Pressure Sensor