Design and Fabrication of a MEMS-Array Pressure Sensor System for Passive Underwater Navigation Inspired by the Lateral Line

by

Stephen Ming-Chang Hou

M.Eng., Electrical Engineering and Computer Science
Massachusetts Institute of Technology, 2004

S.B., Electrical Science and Engineering
Massachusetts Institute of Technology, 2003

S.B., Physics
Massachusetts Institute of Technology, 2003

Submitted to the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the degree of

Electrical Engineer

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2012

© Massachusetts Institute of Technology 2012. All rights reserved.
Design and Fabrication of a MEMS-Array Pressure Sensor System for Passive Underwater Navigation Inspired by the Lateral Line

by

Stephen Ming-Chang Hou

Submitted to the Department of Electrical Engineering and Computer Science on March 14, 2012, in partial fulfillment of the requirements for the degree of Electrical Engineer

Abstract

An object within a fluid flow generates local pressure variations that are unique and characteristic to the object’s shape and size. For example, a three-dimensional object or a wall-like obstacle obstructs flow and creates sharp pressure gradients nearby. Similarly, unsteady flow contains vortical patterns with associated unique pressure signatures. Detection of obstacles, as well as identification of unsteady flow features, is required for autonomous undersea vehicle (AUV) navigation. An array of passive underwater pressure sensors, with their ability to “touch at a distance” with minimal power consumption, would be able to resolve the pressure signatures of obstacles in the near field and the wake of objects in the intermediate field. As an additional benefit, with proper design, pressure sensors can also be used to sample acoustic signals as well.

Fish already have a biological version of such a pressure sensor system, namely the lateral line organ, a spatially-distributed set of sensors over a fish’s body that allows the fish to monitor its hydrodynamic environment, influenced by the external disturbances. Through its ability to resolve the pressure signature of objects, the fish obtains “hydrodynamic pictures”.

Inspired by the fish lateral line, this thesis describes the development of a high-density array of microelectromechanical systems (MEMS) pressure sensors built in KOH-etched silicon and HF-etched Pyrex wafers. A novel strain-gauge resistor design is discussed, and standard CMOS/MEMS fabrication techniques were used to build sensors based on the strain-gauge resistors and thin silicon diaphragms. Measurements of the diaphragm deflection and strain-gauge resistance changes in response to changes in applied external pressure confirm that the devices can be reliably calibrated for use as pressure sensors to enable passive navigation by AUVs. A set of sensors with millimeter-scale spacing, 2.1 to 2.5 μV/Pa sensitivity, sub-pascal pressure resolution, and −2000 Pa to 2000 Pa pressure range has been demonstrated. Finally, an integrated circuit for array processing and signal amplification and to be fabricated with the pressure sensors is proposed.

Thesis Supervisor: Jeffrey H. Lang
Title: Professor of Electrical Engineering
Acknowledgments

This thesis would not have been possible without the efforts of many people. First, I would like to express gratitude to my advisor, Prof. Jeff Lang, for the opportunity to work under his mentorship throughout my graduate studies. His deep intuition and focus on important questions will always influence me. I thank the other faculty under whom I have worked on various projects over the years, Profs. Franz Hover, Marty Schmidt, Alex Slocum and Michael Triantafyllou, for their creative insights and guidance. Their boundless supply of energy, enthusiasm and knowledge make MIT such an incredible place to study.

I would like to thank the other members of the Underwater Sensors Group and the Precision Engineering Research Group. I am grateful to my officemate Dr. Vicente Fernandez, who worked on complementary aspects of our overall project, for our conversations and mutual encouragement. I am especially thankful to Drs. Hong Ma, Alexis Weber and James White for their many hours showing me the ropes in the lab when I first started, and generously providing many pieces of advice throughout, even when they were busy preparing to graduate. Drs. Jian Li, Joachim Sihler and Xue’en Yang also extended invaluable tips on fabrication techniques.

I would like to thank other members of the MEMS community at MIT. In particular, I thank Prof. Joel Voldman for sharing his experience with HF etching. I would like to thank Kevin Nagy and Dr. Nikolay Zaborenko for their bonding recipes, and countless other fabrication laboratory users for sharing bits of advice, which has motivated me to contribute to our collective knowledge.

In the spirit of the collaborative nature of MIT, I thank Drs. Steve Bathurst, Jerry Chen, Ivan Nausieda and Vanessa Wood for sharing their laboratory equipment for experimenting with printable electronics.

I would like to express great appreciation for the MIT Microsystems Technology Laboratories (MTL), i.e. my second home, where my fabrication work was carried out. In particular, I am grateful to MTL staff members Bernard Alamariu, Bob Bicchieri, Kurt Broderick, Eric Lim, Kris Payer, Dave Terry, Paul Tierney, Tim Turner and Dennis Ward, who patiently trained me on each of the machines, maintained tools around the clock, answered my calls and e-mails when I needed help, and offered advice.
I thank Pierce Hayward for training me to use the Zygo profilometer. I am also grateful to Wayne Ryan and Steve Turschmann for building various equipment that my research required.

I would like to thank the National Science Foundation, the NOAA MIT Sea Grant College Program (project grant R/RT-2/RCM-17), the MIT-Singapore Alliance, the MIT Deshpande Center and the MIT Department of Electrical Engineering and Computer Science (EECS) for their funding of my research.

I would like to thank Sam Chang, Dr. Shahriar Khushrushahi, Adam Reynolds, Yasu Shirasaki and my family for taking the time to read my thesis and offer improvements, especially on short notice. However, any outstanding errors are mine alone.

Of course, I am grateful to those at MIT who have provided me with a life outside the lab. I will always remember my friends from the Graduate Student Council, the EECS Graduate Students Association, the Resources for Easing Friction and Stress and Ashdown House for inspiring a selfless sense of community and belonging. I also appreciate the EECS department, the Educational Studies Program and BLOSSOMS for the distinct privilege of teaching bright young people on behalf of MIT.

Finally, I would like to thank my family for their unwavering support and encouragement. I am indebted to my parents’ dedicated efforts in providing me the opportunities I’ve had throughout my life. Their eternal love and faith in me will be carried to future generations. I dedicate this thesis to them.
Contents

1 Introduction .................................................. 21
   1.1 The Fish Lateral Line and Biomimetics ..................... 24
   1.2 MEMS Pressure Sensors: A Broader Context .................. 27
   1.3 Where This Work Fits In ................................... 32
   1.4 Project Summary ........................................... 35
   1.5 Thesis Organization ....................................... 37

2 Device Design ................................................. 39
   2.1 Overview of Device Features ................................. 40
   2.2 Wafer-Level Design ........................................ 43
      2.2.1 Air channels ........................................... 43
      2.2.2 Round 1 ............................................... 44
      2.2.3 Round 2 ............................................... 45
      2.2.4 Round 3 ............................................... 48
      2.2.5 Round 4 ............................................... 50
      2.2.6 Round 5 ............................................... 50
   2.3 Properties of Silicon .................................... 52
      2.3.1 Crystalline structure of silicon ....................... 52
      2.3.2 The elastic properties of silicon .................... 53
      2.3.3 The elastic properties of thin silicon diaphragms .... 55
   2.4 Wheatstone Bridge Circuit ................................ 57
   2.5 Piezoresistive Pressure Sensors ............................. 60
   2.6 Mechanical Model of the Diaphragm ......................... 64
CONTENTS

2.6.1 Diaphragm assumptions ........................................ 64
2.6.2 Governing equations ........................................... 65
2.6.3 The nature of the deflection function ......................... 67
2.6.4 Deflection as a function of pressure ......................... 68
2.6.5 Strain as a function of pressure .............................. 70
2.6.6 Stress as a function of pressure ............................. 71
2.7 Strain-Gauge Resistors ........................................... 73
2.7.1 Relative change in resistance of an infinitesimally small resistor ... 73
2.7.2 Simulating resistance change ................................. 74
2.7.3 Strain-gauge resistor pattern ................................. 78
2.8 Sensitivity ...................................................... 80
2.9 Dynamics ...................................................... 82
2.10 Summary of Expected Performance ............................ 84

3 Fabrication ..................................................... 85
3.1 Overview of Fabrication of Round 4 Devices ................... 86
3.2 Variations on Fabrication for Rounds 1, 2, 3a and 3b ............ 90
3.3 Photolithography .............................................. 92
3.4 Potassium Hydroxide Etching of (100) Silicon .................... 95
3.4.1 Silicon nitride mask and silicon oxide etch stop ............... 96
3.4.2 Finding the crystalline plane ................................ 98
3.4.3 Mechanical wafer protection ................................. 99
3.5 Pyrex Etching .................................................. 102
3.5.1 Substrate material ........................................... 102
3.5.2 Process flow for etching Pyrex .............................. 102
3.5.3 Process design for etching Pyrex ............................ 107
3.5.4 Masking materials .......................................... 107
3.5.5 Pyrex etchants .............................................. 109
3.5.6 Importance of retaining photoresist on gold .................. 109
3.6 Anodic Bonding ............................................... 111
CONTENTS

3.7 Process Design ......................................................... 113
  3.7.1 Order of key steps ................................................. 113
  3.7.2 Placement of insulating oxide growth step ....................... 115
  3.7.3 Open access to cavities ........................................... 115
  3.7.4 Wet processing bonded wafers .................................... 116

3.8 Mask Design ............................................................. 117
  3.8.1 List of masks ....................................................... 117
  3.8.2 Mask alignment ..................................................... 117

4 Measurements ............................................................ 121
  4.1 Photographs of Devices ............................................... 122
  4.2 Instrumentation ....................................................... 126
    4.2.1 Manometer ....................................................... 126
    4.2.2 Zygo profilometer ............................................... 128
    4.2.3 Off-wafer differential amplifiers ............................... 129
    4.2.4 Tech-Etch cable ................................................ 131
    4.2.5 Water-level probe .............................................. 132
  4.3 Deflection ............................................................. 134
  4.4 Drifting Signals ...................................................... 141
    4.4.1 Experimental set up ............................................. 141
    4.4.2 Dummy bridge ................................................... 142
    4.4.3 E&M interference ................................................. 142
    4.4.4 Fluctuating pressure .......................................... 143
    4.4.5 Unstable contact resistance .................................. 144
    4.4.6 Stabilizing the contact resistance .............................. 144
    4.4.7 Gold on chromium .............................................. 147
  4.5 External Bridge Measurements from Isolated Sensors .............. 148
  4.6 Underwater Testing .................................................. 159
    4.6.1 Out-of-water tests .............................................. 160
    4.6.2 Bucket tests .................................................... 161
CONTENTS

4.7 Summary of Measurements .............................................. 163

5 Concluding Remarks ...................................................... 165
  5.1 Summary .................................................................. 166
  5.2 Contributions and Conclusions ..................................... 168
  5.3 Future Work ............................................................. 170
    5.3.1 Further testing of Round 4 devices ......................... 170
    5.3.2 Improved strain-gauge design ................................. 170
    5.3.3 Integrated amplifier and array read-out circuitry ......... 172
    5.3.4 Flexible substrates ............................................. 177

A Chemical Formulas ......................................................... 181

B Standard Operating Procedures ......................................... 183
  B.1 Mask-Making ............................................................ 184
  B.2 TRL Photolithography ................................................. 185
    B.2.1 Double-sided PR ............................................... 187
    B.2.2 With paint ....................................................... 187
  B.3 KOH Etching ............................................................. 188
  B.4 Post-KOH Clean ......................................................... 190
  B.5 Hot Phosphoric ........................................................ 192
    B.5.1 ICL hot phosphoric ............................................. 192
    B.5.2 TRL acid hood ................................................. 192
  B.6 EV510 and Anodic Bonding ......................................... 194

C Process Flows ................................................................. 197
  C.1 Standard Photolithography .......................................... 198
  C.2 Finding the Crystalline Plane for (100) Silicon ................ 199
  C.3 Strain-Gauge Silicon Sensors Without Transistors .......... 200
  C.4 Strain-Gauge Silicon Sensors With Transistors .............. 204
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>D Masks</td>
<td>209</td>
</tr>
<tr>
<td>E Apparatus</td>
<td>223</td>
</tr>
<tr>
<td>F MATLAB</td>
<td>229</td>
</tr>
</tbody>
</table>
List of Figures

1-1 Finnegan the RoboTurtle. ......................................................... 22
1-2 Fish behaviors mediated by the lateral line. .............................. 23
1-3 Typical locations for the lateral lines in fish. ............................ 25
1-4 Cross-section and plan view of a typical bulk micromachined piezoresistive pressure sensor. ......................................................... 29
1-5 Cross-section of a typical silicon/Pyrex capacitive pressure sensor. .... 30
1-6 The Druck resonant pressure sensor. ........................................ 30
1-7 Principal mechanical properties of a sensor as functions of diaphragm thickness and length. ......................................................... 31
1-8 Four potential applications of the biomimetic pressure sensor array system. 33

2-1 Diagram of pressure-sensor array with basic structure depicted. .... 40
2-2 Side view of a single sensor. ..................................................... 42
2-3 Schematic of air channels for underwater sensors. ...................... 44
2-4 Overlay of Round 1 devices. ................................................... 46
2-5 Layout of resistors from Rounds 2 and 3. .................................. 47
2-6 Overlay of Round 3b devices. .................................................. 49
2-7 Overlay of Round 4 devices. .................................................... 51
2-8 Crystal planes and major directions. ........................................ 52
2-9 Crystal orientation in (100) silicon wafers. ............................... 53
2-10 The Wheatstone bridge circuit. .............................................. 57
## LIST OF FIGURES

2-11 Four resistors along a \(\langle 110\rangle\) direction at the centers of the four edges of the surface of a square diaphragm. ........................................ 61

2-12 A square diaphragm of length \(L\) and thickness \(H\). ......................... 65

2-13 The strain of the top surface of the diaphragm in the \(x\) direction \((\epsilon_x)\) as a function of normalized positions. ........................................ 75

2-14 The local optimal resistor lengthwise orientation for maximizing resistance change. ......................................................... 76

2-15 The sign of the resistance change when a local resistor is placed in the optimal direction. .................................................. 77

2-16 The design of four strain-gauge resistors on a square diaphragm. ............ 79

3-1 Standard photolithography. ...................................................... 93

3-2 Mask-making process. .......................................................... 94

3-3 Examples of KOH-etching \((100)\) silicon. ........................................ 97

3-4 Side view of KOH wafer holder. ............................................... 100

3-5 Two-sided alignment mechanism. ............................................. 118

3-6 Mask alignment marks. .......................................................... 119

4-1 Device from Round 1 (silicon diaphragm without strain-gauge resistors). .... 122

4-2 An entire wafer from Round 2 (strain-gauge resistors on dummy nitride wafer). 123

4-3 An entire wafer from Round 3 (isolated strain-gauge sensors). ................. 124

4-4 An entire wafer from Round 4 (interconnected sensors). ....................... 125

4-5 Manometer used to control the pressure in the cavities of devices from Rounds 1 and 3. ......................................................... 127

4-6 Photograph of the Zygo profilometer. ......................................... 128

4-7 Circuit diagram of off-wafer differential amplifier. ........................... 129

4-8 Static and frequency responses of off-wafer differential amplifiers. ......... 130

4-9 Photograph of the head of the Tech-Etch cable. .............................. 131

4-10 Photograph of the water-level probe (sideways). .............................. 132

4-11 Voltage vs. pressure to calibrate the water-level probe. ........................ 133
LIST OF FIGURES

4-12 Profiles of a 2828 µm diaphragm at a pressure of −1500 Pa. 134
4-13 Profiles of a 2828 µm diaphragm at a pressure of +1500 Pa. 135
4-14 The deflection of the center of the diaphragm at various pressures for two different sizes. 139
4-15 The deflection of the center of the diaphragm at various pressures for a 4000 µm diaphragm. 140
4-16 Experimental set up for testing one strain-gauge resistor. 142
4-17 The amplified output of an external bridge testing a single resistor on a 4000 µm diaphragm over an 80-second period. 143
4-18 Contact resistance stabilized by regular epoxy and microscope probe needle tips. 146
4-19 Contact resistance stabilized by WEST SYSTEM® epoxy and microscope probe needle tips. 146
4-20 Contact resistance stabilized by both types of mechanical epoxies and microscope probe needle tips. 147
4-21 The output of an external bridge from a 4000 µm diaphragm undergoing ±1600 Pa changes. 149
4-22 The output of an external bridge from a 4000 µm diaphragm undergoing ±200 Pa changes. 150
4-23 The output of an external bridge from a 4000 µm diaphragm undergoing a 200 Pa step. 151
4-24 External bridge voltage vs. pressure for various resistors from a 4000 µm diaphragm. 152
4-25 External bridge voltage vs. pressure for various resistors from a 2828 µm diaphragm. 153
4-26 External bridge voltage vs. pressure for various resistors from another 2828 µm diaphragm. 154
4-27 External bridge voltage vs. pressure for various resistors from a 2000 µm diaphragm. 155
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-28</td>
<td>External bridge voltage vs. pressure for various resistors from another 2000 µm diaphragm.</td>
<td>156</td>
</tr>
<tr>
<td>4-29</td>
<td>Photograph of a mounted wafer with pressure sensors that can be used underwater (Round 4).</td>
<td>159</td>
</tr>
<tr>
<td>4-30</td>
<td>Sample trace of two pressure sensors 2 cm apart (Round 4) activated by air gun swiped across wafer.</td>
<td>160</td>
</tr>
<tr>
<td>4-31</td>
<td>Bucket set up.</td>
<td>161</td>
</tr>
<tr>
<td>4-32</td>
<td>Resonant bucket waves.</td>
<td>162</td>
</tr>
<tr>
<td>5-1</td>
<td>Interconnect wiring of an array of pressure-sensing cells.</td>
<td>172</td>
</tr>
<tr>
<td>5-2</td>
<td>Schematic of the integrated transistor amplifier and array read-out circuitry for a 2 × 2 array.</td>
<td>173</td>
</tr>
<tr>
<td>5-3</td>
<td>Layout of one cell of the integrated transistor amplifier and array read-out circuit.</td>
<td>174</td>
</tr>
<tr>
<td>5-4</td>
<td>Side view of the strain-gauge pressure sensor with integrated transistor amplifier and array read-out circuitry.</td>
<td>175</td>
</tr>
<tr>
<td>5-5</td>
<td>Diagram and photograph of the elastomer-based pressure sensors described in [96].</td>
<td>178</td>
</tr>
<tr>
<td>5-6</td>
<td>Diagram of the three-terminal squitch described in [64].</td>
<td>179</td>
</tr>
<tr>
<td>D-1</td>
<td>Mask P (Rounds 1 and 3a).</td>
<td>210</td>
</tr>
<tr>
<td>D-2</td>
<td>Mask N (Rounds 1 and 3a).</td>
<td>211</td>
</tr>
<tr>
<td>D-3</td>
<td>Mask M (Rounds 1 and 3a).</td>
<td>212</td>
</tr>
<tr>
<td>D-4</td>
<td>Mask D (Round 1).</td>
<td>213</td>
</tr>
<tr>
<td>D-5</td>
<td>Mask R (Rounds 2, 3a and 3b).</td>
<td>214</td>
</tr>
<tr>
<td>D-6</td>
<td>Mask D (Round 3a).</td>
<td>215</td>
</tr>
<tr>
<td>D-7</td>
<td>Mask P (Round 3b).</td>
<td>216</td>
</tr>
<tr>
<td>D-8</td>
<td>Mask O (Round 3b).</td>
<td>217</td>
</tr>
<tr>
<td>D-9</td>
<td>Mask D (Round 3b).</td>
<td>218</td>
</tr>
<tr>
<td>D-10</td>
<td>Mask P (Round 4).</td>
<td>219</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-11</td>
<td>Mask O (Round 4)</td>
<td>220</td>
</tr>
<tr>
<td>D-12</td>
<td>Mask D (Round 4)</td>
<td>221</td>
</tr>
<tr>
<td>D-13</td>
<td>Mask R (Round 4)</td>
<td>222</td>
</tr>
<tr>
<td>E-1</td>
<td>KOH wafer holder: bottom view of bottom piece.</td>
<td>224</td>
</tr>
<tr>
<td>E-2</td>
<td>KOH wafer holder: bottom view of top piece.</td>
<td>225</td>
</tr>
<tr>
<td>E-3</td>
<td>KOH wafer holder: top view of top piece.</td>
<td>226</td>
</tr>
<tr>
<td>E-4</td>
<td>Tech-Etch cable.</td>
<td>227</td>
</tr>
</tbody>
</table>
LIST OF FIGURES
List of Tables

2.1 Piezoresistive coefficients along a $\langle 110 \rangle$ direction for both types of doped silicon. 60
2.2 Expected performance parameters for strain-gauge pressure sensors of various
diaphragm lengths $L$. 84
3.1 Variations on fabrication for Rounds 1, 2, 3a, 3b and 4. 91
3.2 Diagram of cross-sectional trench profiles from different types of etch methods. 95
3.3 Process flow for etching Pyrex wafers. 104
4.1 Slopes $c_1/P$ for various diaphragm lengths $L$. 136
4.2 Experimental values of slopes of best-fit lines for amplified voltage vs. pressure for strain-gauge resistors on various diaphragms from Round 3b. 157
4.3 Theoretical values of slopes of best-fit lines for amplified voltage vs. pressure for strain-gauge resistors on various diaphragms from Round 3b. 157
A.1 Chemical formulas and full names. 181
B.1 Recipe for bonding silicon and Pyrex. 195
C.1 Process flow for standard single-sided photolithography. 198
C.2 Process flow for standard double-sided photolithography. 198
C.3 Process flow for finding the crystalline plane for $\langle 100 \rangle$ silicon. 199
C.4 Process flow for Pyrex wafers for strain-gauge silicon sensors without transistors. 201
C.5 Process flow for SOI wafers for strain-gauge silicon sensors without transistors. 201
LIST OF TABLES

C.6 Process flow for SOI wafers for strain-gauge silicon sensors without transistors

(cont.) ................................................................. 202

C.7 Remainder of process flow for strain-gauge silicon sensors without transistors. 203

C.8 Process flow for Pyrex wafers for strain-gauge silicon sensors with transistors. 205

C.9 Process flow for SOI wafers for strain-gauge silicon sensors with transistors. 206

C.10 Process flow for SOI wafers for strain-gauge silicon sensors with transistors

(cont.) ................................................................. 207

C.11 Process flow for SOI wafers for strain-gauge silicon sensors with transistors

(conc.) ................................................................. 207

C.12 Remainder of process flow for strain-gauge silicon sensors with transistors. 208

D.1 List of masks used for each round of devices. ........................................ 209
Chapter 1

Introduction

Many methods of sensing have been used by undersea vehicles to obtain three-dimensional mappings of the surrounding ocean floor, walls and other objects. Such maps aid vehicles in navigating through unfamiliar territory, avoiding collisions with moving objects, and surveilling the environment. The most common methods—sonar, radar and optical sensing—require active transceivers and thus use significant amounts of power. For small autonomous undersea vehicles (AUVs), such as the one depicted in Figure 1-1, space and energy are precious as energy must be stored on board and should be reserved for motion, especially propulsion. Additionally, in cluttered environments or poor visibility conditions such as murky surf zones, topological mapping by sonar or optical sensing becomes difficult as signal to noise is drastically reduced and the process depends strongly on the acoustic environment (e.g., multipath). Furthermore, the required equipment may occupy much of the payload space of the vehicle. Therefore, a simple compact passive sensing system that does not require high power would be ideal for such vehicles.

One domain where passive sensing can be achieved is fluid pressure. An object within a fluid flow generates local pressure variations that are unique and characteristic to the object’s shape and size. For example, a three-dimensional object or a wall-like obstacle obstructs flow and creates sharp pressure gradients nearby. Similarly, unsteady flow contains vortical patterns with associated unique pressure signatures. Detection of obstacles, as well as identification of unsteady flow features, is required for vehicle navigation. An array
of passive underwater pressure sensors, with their ability to “touch at a distance” with minimal power consumption, would be able to resolve the pressure signatures of obstacles in the near field and the wake of objects in the intermediate field. As an additional benefit, with proper design, pressure sensors can also be used to sample acoustic signals as well.

Fish already have a biological version of such a pressure sensor system, namely the lateral line organ, and this thesis is inspired by their approach. The blind Mexican cavefish, *Astyanax fasciatus*, can form full real-time three-dimensional maps of its surroundings to move in unfamiliar environments at high speeds without collisions [59, 89]. Unlike the electrolocation sense found in some species of fish, *A. fasciatus* accomplishes this surprising feat without the use of electric fields, and instead relies primarily on its lateral line organ. While all fish have this organ, not all use it to the extent that the blind cavefish does [59].

The lateral line is a spatially-distributed set of sensors over a fish’s body that allows the fish to monitor its hydrodynamic environment, influenced by external disturbances. Through its ability to resolve pressure signatures of objects, the fish obtains “hydrodynamic pictures”, enabling the lateral line to act like a “touch at a distance” device.

Many other lateral-line-mediated behaviors in fish have been identified by biologists [67, 89], including (a) rheotaxis, or orienting themselves to currents and holding stationary in
strong currents; (b) detecting, localizing and tracking prey by their wake; (c) communicating with other fish; (d) matching their own swimming speed and direction to that of their neighbors while performing tight and rapid schooling maneuvers; (e) recognizing nearby physical objects; and (f) swimming efficiently. These behaviors are depicted in Figure 1-2.

In the world of AUVs, there is currently no pressure sensing equivalent to the lateral line organ. However, with its diverse capabilities in nature, the lateral line has advantageous features to offer AUV navigation technology.

This thesis is part of ongoing work toward the development of high-density arrays of microelectromechanical systems (MEMS) pressure sensors to enable passive navigation by AUVs. Inspired by the fish lateral line, we are developing inexpensive, low-power sensors that passively measure static and dynamic pressure fields around an AUV with sufficient spatial and time resolution to detect and map objects generating the hydrodynamic disturbance. Related projects within our research group include the development of processing
CHAPTER 1. INTRODUCTION

schemes that use the sensors pressure information to detect, identify and classify objects in the flow environment for AUV navigation and control [32, 30, 31]. Combining the sensors and processing software not only emulate but also extend the capabilities of the lateral line in fish. The sensor arrays will be capable of detecting near-field flow patterns and near- and far-body obstacles and vehicles, as well as mapping near-body objects. This would be a unique capability for navigation in shallow water and/or cluttered environments, for use with multiple AUVs, and for flow control in conventional and biomimetic\textsuperscript{1} vehicles. Another application of our sensor is to determine the pressure distribution on the propellors, sails and hulls of sea vehicles for optimizing design and improving performance. We envision that at the end of these projects, these sensors will emerge as a standard, low-cost system available in most AUVs.

While this thesis focused on implementing a sensor system using rigid and flat silicon, we eventually want to build a system using flexible or custom-shaped soft polymer materials, which would enable users to place a sensor system flush against curved surfaces, such as fins and hulls. Furthermore, silicon is brittle whereas polymers can be quite robust. Polymers could be a better choice for the mechanically rough undersea environment. With these future directions in mind, we designed a silicon-based sensor with technical approaches that can be easily transferred to polymer-based technology. For example, while piezoresistive sensors are widely used to build silicon sensors, this technique does not work in polymers. Instead, we chose to develop a strain-gauge sensor. Based on this concept, members of our research group have explored fabricating underwater pressure sensor arrays using conductive polymers [96].

1.1 The Fish Lateral Line and Biomimetics

The basic sensory unit of the fish lateral line organ is the neuromast, which is a collection of drag-based flow velocity sensors. Neuromasts are used in two manners. First, they are distributed on the surface of the fish and protrude directly into the open water. In this

\textsuperscript{1}Biomimetics is the study of biological systems as models for the design of engineered materials and machines.
arrangement, the neuromasts are directly stimulated by the local fluid velocity to sense flow. As shown in Figure 1-3, the specific distribution of neuromasts varies widely from species to species. Second, the neuromasts are enclosed in canals with pores that open to the outside flow periodically [34]. These canals have been described as an array of pressure gradient sensors [20], where a pressure difference between adjacent pores drives fluid motion in the canal, and thereby stimulates the neuromasts. Studies that selectively deactivated the canals found that the mapping abilities of the lateral line appear to be predominantly accomplished by its canal system [59]. By measuring the pressure gradient as a function of location along the fish’s body and time, the fish is able to locate and identify nearby objects as well as determine their shapes and velocities.

While the lateral line organ cannot be identically implemented with standard fabrication technologies, the capabilities similar to that of the lateral line would greatly benefit AUVs. In particular, the ability to locate and obtain information about nearby obstructions is increasingly important as AUVs are finding applications in cluttered environments and surf zones. Also, the ability for flow mapping and identifying vortical structures allows the possibility for optimizing control and navigation in unsteady environments. In addition to
these capabilities, a distributed pressure sensor system would be completely passive and consequently require little power. Compared to active systems like sonar, the primary disadvantage of a pressure sensor system would be its limited range, or the maximum distance of detected objects.

A number of researchers have experimentally and numerically studied the fish’s lateral line and its ability to identify objects and flow structures. In investigating the blind fish’s object sensing skills, [89] constructed a model neuromast and demonstrated the neuromast’s ability to locate plates and thin beams at a distance of 2 mm. [40, 41] measured the dynamic pressure distributions generated on the body of a model fish when gliding alongside and into a wall at similar millimeter-scale distances. [87] showed that goldfish use their lateral line to detect and discriminate the size, velocity and shape of passing rods in still water. Numerical experiments by [79] demonstrated that an array of pressure sensors could track the position and circulation in a channel. While free stream flows are more complex and unpredictable in open water than single vortices are, [79] established that an array of pressure sensors is a viable way to identify and track vortices. The question remains how well a simple pressure sensor array is able to distinguish between moving objects of different shapes and sizes.

Our group has used commercial pressure sensors separated on the order of 10 millimeters to record pressure signals resulting from flow around both still and moving objects. Using principal component analysis (PCA) and Kalman filtering on the recorded signals, we could discriminate between various cylindrical objects with round and square cross-sections of sizes on the order of several centimeters. Similarly, we could track motion up to half a meter per second using commercial pressure sensors separated on the order of several millimeters apart. We found that a classification error rate of under 2% can be achieved with a 2 kPa range, 10 Pa resolution, and 60 Hz data acquisition rate [30, 31, 23]. The pressure sensor spacing would need to be on the order of millimeters in order to capture the relevant features in a single instance, which would be necessary under non-uniform conditions found outside laboratory conditions.
1.2 MEMS Pressure Sensors: A Broader Context

Microelectromechanical systems (MEMS)\(^2\) are micro-scale devices that enable the operation of complex systems by converting physical stimuli from the mechanical, thermal, chemical and optical domains to the electrical domain. MEMS engineers engage technologies across a wide set of scientific disciplines, including physics, chemistry, material science, integrated circuit (IC) fabrication and manufacturing. Due to its origins from the IC industry, much of MEMS technology is based on silicon, the substrate material used for the vast majority of commercial electronics. However, there is ongoing research in other materials as well, such as plastics and ceramics, for their lower costs and biocompatibility for medical applications.

As a result of its interdisciplinary nature, MEMS technology has found use in many industries, especially automotive, medical and aerospace. A device class where MEMS have thrived is sensing. For example, early crash sensors for airbag safety systems were merely mechanical switches. Today, airbag systems use MEMS sensors that not only measure acceleration, but also provide self-diagnostics and integration with other sensors in the vehicle. Other types of MEMS sensors currently undergoing rapid research progress include flow sensing for biomedical applications [3], microphones for portable devices [72], and accelerometers for touch screens and gaming [35, 69].

After accelerators, pressure sensors are the most commercially successful class of MEMS sensors. These devices employ a broad range of techniques to convert mechanical pressure into electrical signals, such as piezoresistive, capacitive, resonant, and strain-gauge resistive sensing. Furthermore, the list of applications of pressure sensors has also grown tremendously over the past three decades. As a result, pressure sensing has developed into a market where highly specialized devices can be found for specific needs. The fundamental specification of a pressure sensor is its operating pressure range. Other obvious parameters, such as physical dimensions, pressure resolution, reliability, lifespan, environmental compatibility and cost are also important, but there are more subtle considerations as well.

\(^2\)Microelectromechanical systems is the term most commonly used in the United States. In Europe, the technology is generally known as microsystems technology (MST), whereas in Japan, the term micromachines is used in English-language publications. This thesis follows the U.S. convention.
The effects of temperature, long-term drift, hysteresis, linearity, and the dynamic response all influence the design and fabrication of a custom-made pressure sensor.

A popular design feature of pressure sensors is a micromachined flexible diaphragm. Depending on the application, such diaphragms range from tens to thousands of microns in width and from a few to hundreds of microns in thickness. Various types of diaphragm-based pressure sensors, such as piezoresistive, capacitive, resonator, and strain-gauge resistive sensors, are discussed in the remainder of this section. While the ultimate goal of the project is to implement pressure sensors in a soft or moldable material, we first tested sensor designs in silicon with technology that would also work with polymers.

Diaphragm-based pressure sensors rely on mechanical deformation of the diaphragm to alter the electrical properties of a sensing component on the diaphragm. Piezoresistive and strain-gauge resistive pressure sensors detect changes to resistance. Specifically, the resistance of a resistor with length \( l \), cross-sectional area \( A \) and resistivity \( \rho \) is \( R = \rho \frac{l}{A} \). Thus, there are two categories by which the resistance can change in response to strain: changes to the geometry (\( l \) or \( A \)) or changes to the conductive properties (\( \rho \)) of the resistor. The predominant cause of resistance change depends on the material. In metals, shape deformation, and thus changes to \( l \) and \( A \), are the primary source of resistance change, leading to strain gauges. In silicon, \( \rho \) is affected by stress, and thus by strain, causing changes to \( R \). This effect is called piezoresistivity, and electrical elements of this type are called piezoresistors.

Piezoresistive pressure sensors have resistors implanted on the diaphragm. When a pressure difference between the two faces of the diaphragm deforms the diaphragm, the strain is translated into a change in resistance. An example of a piezoresistive pressure sensor is shown in Figure 1-4. As will be discussed later in Section 2.5, the four resistors are located at the centers of the edges of the square diaphragm and are oriented in the same direction. One common application of piezoresistive pressure sensors is in the automotive industry, such as measuring diesel injection pressure and controlling exhaust gas recirculation systems. The major drawback to this technology is that the diaphragm is restricted to materials that have strong piezoresistive properties.
A capacitor with one electrode attached to the flexible diaphragm can also sense pressure via changes in its capacitance. An example of a capacitive pressure sensor is shown in Figure 1-5. Typical advantages of capacitive sensors include high sensitivity, low power consumption, and low temperature dependence. Also, capacitive sensors have been demonstrated in non-silicon materials, such as quartz and polymers [3, 60]. Unfortunately, depending on the specifics of the geometry of the devices and pressure range, there may be issues with hysteresis and static friction, or stiction. Furthermore, capacitive sensors tend to have nonlinear outputs and require complex electronics. To counter these problems, some implementations, such as intravascular blood pressure measurement and intracranial pressure [3], use multiple sensors to obtain a single pressure measurement. Since our applications require an array of sensors, where each sensor produces a reliable local reading, capacitive sensing is not a suitable option.

Resonant pressure sensors rely on a resonating mechanical structure to detect diaphragm deformation. One of the earliest such sensors, commercialized by Druck, is shown in Figure 1-6. High-performance resonant pressure sensors are particularly useful for high-pressure applications in the oil and gas industry, where accurate pressure measurement is essential [3]. Although the performance specifications can be quite impressive, the most attractive materials for resonant sensors, such as quartz, are incompatible with integrated circuits, which
CHAPTER 1. INTRODUCTION

is necessary for efficient addressing by an array of sensors. Other resonant pressure sensors measure the changes in electromagnetic resonant structures, such as inductor-capacitor (LC) cavities for tuning wireless electronics [46]. The concept is also used in medical engineering: CardioMEMS is developing devices that are passive LC resonator circuits and can be implanted in the patients heart chambers or into the pulmonary artery [18].

Finally, we consider the sensitivity and possible applications of diaphragm-based resistive strain-gauge sensors. Figure 1-7 shows the maximum deflection, maximum stress, maximum strain and lowest natural frequency of a square silicon diaphragm as functions
1.2. MEMS PRESSURE SENSORS: A BROADER CONTEXT

Figure 1-7: Principal mechanical properties of a sensor as functions of diaphragm thickness and length. Values are given for a pressure difference of 10 Pa. The nominal design is shown with circles.

of the primary geometric parameters of diaphragm: side length and thickness. Here, we assume that the diaphragm acts as a homogeneous plate with stiff boundaries at the edges that experiences a nominal gauge pressure of 10 Pa, the stagnation pressure associated with a flow of 14 cm/s. The deflection, stress and strain vary approximately linearly with pressure, and can therefore be scaled as needed. Indicated on each contour plot is the nominal design of a square diaphragm with a diameter of 2 mm and a thickness of 20 μm. The graphs confirm the strong variation in sensor properties with geometry. As expected, stiffness of the membrane increases dramatically with thickness, and inversely with diameter.

The stress and strain sub-plots show the maximum values, which occur at the center of the edges of the diaphragm, i.e. at the four points halfway between adjacent corners of the diaphragm. If the ultimate strength of silicon is conservatively estimated to be
300 MPa, the nominal design is safely stressed for pressures approximately four orders of magnitude larger than the 10 Pa considered here, or 100 kPa. This compares favorably with commercial hydrophones available today, which have a typical overpressure in the range of 200 dB relative to 1 µPa, or 10 kPa. Furthermore, the fundamental natural frequency of the nominal pressure-sensing diaphragm is quite high, in the range of tens or hundreds of kilohertz. This frequency vastly exceeds the frequencies generated by near-field and mid-field pressure disturbances, which are on the order of tens of hertz for many natural and man-made structures, thus avoiding resonance. Acoustic transducers in use today, however, do exceed 1 MHz, namely in Doppler velocimetry loggers (e.g., RD Instruments Workhorse Navigator) and acoustic imaging systems (e.g., DIDSON). For positioning systems, lower frequencies in the neighborhood of 10–30 kHz are common for large-scale, multi-kilometer systems, whereas frequencies of 300 kHz have been used on scales of several hundred meters. Whales and dolphins communicate at frequencies up to 100 kHz. Hence, in addition to pressure sensing, a diaphragm-based sensor will also be capable of operating as a passive acoustic detector for the lower end of frequencies relevant in underwater acoustics.

1.3 Where This Work Fits In

This thesis demonstrates the design, fabrication and testing of MEMS strain-gauge silicon pressure sensor arrays inspired by the fish lateral line to enable passive navigation by AUVs. Figure 1-8 illustrates some of these applications, as well as related tasks that would be enabled by such a system of pressure sensors.

These sensing capabilities are becoming possible with the development of MEMS technology to fabricate arrays containing hundreds or even thousands of pressure sensors. The sensors, each around 2 mm in length, can be arranged over a flat or curved surface in various configurations, such as a single line, a patch consisting of several parallel lines, or specialized forms to fit the hull shape of a vehicle or its fins. The sensors can be packaged closely together at distances of a few millimeters apart to be able to resolve pressure and flow features near the array spacing, which in turn can be used to identify the overall flow features.
Both self-propelled vehicles and obstacles standing within a smooth or turbulent current generate flow disturbances. The near-field of this hydrodynamic disturbance extends typically about one body length around the generating object and is characterized by strong pressure and velocity variations. Such near-body pressure variations are referred to as “pseudo-sound” and can be detected by a sensor which is close to the obstacle. If the disturbance is unsteady and its frequency is sufficiently high, the disturbances generates acoustical waves that create a far-field disturbance, which is detectable at hundreds or thousands of body lengths away, depending on the frequency. In addition, a hydrodynamic wake is shed by the body and is detectable directly downstream from the generating body as pressure and velocity fluctuations in the near and intermediate field, up to hundreds of meters away from the source. The sensors we developed are appropriate to all three of these regimes: pseudo-sound, high-frequency sound, and wakes, although we focused primarily on applications for pseudo-sound and wake flows. For some standard objects, hydrodynamic signatures and flow patterns are codified, so that the sensor system could potentially au-
tomatically detect objects and flow patterns. Our pressure sensor arrays can thus provide the following capabilities to AUVs:

1. Measure the distance to the near-field objects, obstacles and other vehicles.

2. Determine the location, speed, direction and size of moving vehicles and objects.

3. Form accurate topological maps of nearby objects through reconstruction of their shapes from predetermined pressure hydrodynamic signatures.

4. Assist maneuvering in cluttered environments in the presence of turbidity and turbulence, and operations in the dark.

5. Assist in the coordination of multiple robots. Each robot vehicle will be provided at low power with effective images of the location and orientation of the near-by vehicles.

6. Identify flow patterns in the surrounding flow to optimize fin and propulsor performance. This flow information can also be used for energy extraction in biomimetic vehicles.

Other sensing technologies, such as sonar or radar, also use arrays sometimes, but these are limited to a few dozen in number and are centimeters or meters apart. The concept described in this thesis can be scaled to an array of several hundred of sensors, each millimeters apart.

This project is of interest not only to undersea researchers but also to the MEMS community as well. Currently, much of MEMS sensor development is focused on designing single, extremely sensitive sensors for use in applications such as microphones [72]. Furthermore, research in sensor arrays tends to be motivated by tactile applications [78]. From the materials science perspective, undersea navigation provides motivation for MEMS research in flexible, non-silicon substrates. Finally, by successfully demonstrating an array of pressure sensors for undersea object identification, we hope the project will inspire further work in integrating MEMS with macro-scale systems for high-precision applications.
1.4 Project Summary

A MEMS pressure sensor system based on strain gauges bonded to silicon diaphragms was fabricated and tested. The system consists of a set of sensor cells spaced a few millimeters apart fabricated on etched silicon and Pyrex wafers. Silicon and Pyrex are well-understood MEMS substrates that provide a foundation for evaluating the feasibility of transferring our pressure sensor design to polymer substrates. The sensing element on each cell is a set of strain-gauge resistors mounted on a flexible 2-mm wide square diaphragm, which is a thin 20-µm layer of silicon attached at the edges to a square silicon cavity. The physical and electrical dimensions of the sensor components were chosen to satisfy the sensitivity and density specifications of the underwater environment. Finally, the sensors are attached to an array read-out system with sufficient voltage and time resolution to enable data output to a computer for further signal processing.

Several challenges were encountered in this project: read-out of an array of data, electronics for signal-to-noise enhancement, mechanical robustness, the equilibration of the back pressure, dynamics and noise, and compatibility with polymers.

In order to develop a fully functional system ready for open water sensing and navigation, we modularly tested individual aspects of the sensor system under highly controlled environments. However, all tests required the ability to read the array data. Thus, the ability to collect the outputs from the sensor array accurately and at a high data rate (kHz range) was of highest priority. As a first-pass solution, we have a pair of wires coming out of each sensor cell to a standard wire bundle that is fed into a computer. While this is acceptable for a small number of cells (fewer than 50), it is not easily scalable to hundreds or thousands of cells. One scalable solution is inspired by magnetic core memory: with transistor circuits connected to each sensor cell, signals address a particular column of cells, and the output signals from the entire column is returned. This reduces the output wiring to only a few fixed wires. However, while these electronics are conceptually simple, which is critical for moving the sensor design to soft substrates, reliable fabrication and calibration are significant challenges.
Since the undersea environment can be physically and chemically harsh, we designed the sensor system to be robust against possible damages. The design includes safety mechanisms that ensure that the loss of one cell will not affect the operation of the others. Of course, there are trade-offs between simplicity and robustness. We chose and fabricated a reasonable design that allowed us to test the system under controlled environments. In the future, we plan to develop a system that is able to handle more realistic situations but would require more complex electronics or layers of fabrication steps.

Another challenge is the equilibration of back pressure, which is pressure applied to the back-side of the diaphragms from within the sensor cavity. To reliably map flow velocities in the ocean, we are interested in detecting small-scale pressure fluctuations on the order of a few pascals. However, large-scale homogeneous pressure changes, such as those experienced when the entire system moves up or down relative to sea level would overwhelm any relevant signal.\footnote{One meter of water creates approximately 10 kPa, or about 0.1 atm, of large-signal pressure.} Furthermore, the sensors are physically limited in their dynamic range. Diaphragm-based sensors with sensitivity in the pascal range are not able to withstand pressures on the order of $10^5$ Pa without physically breaking or leading to permanent damage. To design a robust sensor with good signal-to-noise, we remove the large-scale DC component of pressure change via a common back pressure. We designed fluidic channels that enable fast equilibration of the back pressure so that our sensors are only detecting spatially varying pressure gradients.

This thesis describes the design, fabrication and static testing of individual MEMS strain-gauge silicon pressure sensors with amplification circuitry off-wafer. The results demonstrate that the proposed technology is feasible for the underwater object detection application described earlier. Remaining issues, including integrated amplifying and array-processing circuitry, dynamic responses, and full array testing underwater are left as future work.
1.5 Thesis Organization

This chapter, Chapter 1, explains the motivation, background and objectives of the thesis. Chapter 2 describes the design of the strain-gauge pressure sensor system. Chapter 3 explains the fabrication design of the device, including wafer etching, photolithography, process flow design and mask design. Chapter 4 contains the device measurements. Chapter 5 summarizes the work presented, conclusions drawn from the project, and suggestions for future directions.

There are several appendices that provide more detailed information relevant to the main text. Appendix A lists chemical formulas for common names and abbreviations used in this thesis. Appendix B contains standard operating procedures during fabrication. Appendix C contains full device process flows. Appendix D shows the masks used during fabrication. Appendix E contains technical diagrams of the various apparatus used in fabrication and measurement. Appendix F contains the MATLAB codes used for design analysis.

Finally, a list of reference materials is provided at the end of this thesis.
Chapter 2

Device Design

This chapter discusses the design of the strain-gauge pressure sensor system. Section 2.1 provides an overview of the device features. Section 2.2 describes the wafer-level features of the various pressure sensor systems fabricated. Section 2.3 describes the properties of silicon relevant for modeling device behavior and designing the fabrication process. Section 2.4 calculates the change in the output voltage of a Wheatstone bridge resulting from small changes in the sense resistances. Section 2.5 discusses a well-known pressure sensor based on piezoresistive properties of silicon, which provides a benchmark against which the strain-gauge pressure sensor is compared. Section 2.6 describes Kirchhoff-Love plate theory, which is the mechanical model for the diaphragms that form the basis of the strain-gauge pressure sensor. Section 2.7 explains the design of the strain-gauge resistors, the sensing element of the devices. Section 2.8 calculates the sensitivity of the pressure sensor, which provides the pressure resolution for a given noise level. Section 2.9 estimates the dynamics of the sensor. Finally, Section 2.10 summarizes the expected performance of the strain-gauge pressure sensor system for various diaphragm sizes.
CHAPTER 2. DEVICE DESIGN

2.1 Overview of Device Features

The strain-gauge pressure sensor system presented in this thesis consists of a set of MEMS pressure sensors with side lengths on the order of 2 mm (2000 µm) spaced a few millimeters apart and fabricated on bonded silicon and Pyrex wafers. The pressure-sensing array was fabricated in silicon and Pyrex for two primary reasons: the structural and electronic properties of these materials, as well as their microfabrication technologies, are stable and well understood. Additionally, silicon offers a controlled environment in which to develop a pressure-sensing array. A future design of the pressure sensor system will take place in polymer materials. The use of a strain gauge instead of silicon-specific technologies, such as piezoresistors, is a design decision that renders the sensor transferrable to polymer-based technologies. These sensors can be arranged over a surface in various piecewise linear configurations, such as a single line, a patch consisting of several parallel lines or specialized forms to approximate the shape of a vehicle’s hull or fins. Figure 2-1 shows one possible configuration for the pressure system.

![Diagram of pressure-sensor array with basic structure depicted.](image)

Each individual pressure sensor has a strain gauge, which is a set of four long and
narrow\(^1\) snaking resistors, mounted on a flexible thin (20 \(\mu\)m) square silicon diaphragm attached at the edges to a square silicon cavity 2000 \(\mu\)m wide on each side. To create a spatially-invariant reference pressure across the array, the cavities are interconnected to one another through channels in both the silicon and Pyrex wafers. As the difference in pressure above and below a particular diaphragm changes, the diaphragm bends\(^2\) and the strain-gauge resistances change. To maximize the pressure sensitivity, the four resistors, each on the order of 10 k\(\Omega\), are connected in a Wheatstone bridge configuration, which is described later in Section 2.4. A side view of one sensor built in a 150-mm diameter silicon-Pyrex wafer pair is shown in Figure 2-2. There are dozens of such sensors on a single pair of wafers. The square diaphragm is the portion of the silicon suspended above the cavity. The four strain-gauge resistors of the Wheatstone bridge sit on the upper electrically insulating silicon oxide layer. The oxide layer at the bottom surface of the diaphragm serves as an etch stop for wet etching the 650-\(\mu\)m thick silicon handle wafer, and the silicon nitride layer that encases the silicon-oxide-silicon sandwich wafer is the etch mask. This etch process is discussed in Section 3.4. While not shown in Figure 2-2, a waterproofing layer can also be added over the resistors to electrically insulate the devices when they are placed underwater.

Each sensor is powered by a common source voltage of 10 V.\(^3\) As calculated later in Section 2.8, the sensitivity of each sensor is thus on the order of 0.087 \(\mu\)V/Pa. Since the thermal noise voltage is near 0.13 \(\mu\)V, the pressure resolution of the sensors is on the order of 1.5 Pa, which satisfies the resolution specification discussed in Chapter 1. The power consumption of each sensor is about 4 \(\mu\)W. If we expect large pressure signals, we can sacrifice pressure resolution and reduce power consumption by lowering the source voltage. Finally, the resonant frequency is 71 kHz, far higher than required for underwater navigation.

The voltage output from the Wheatstone bridges can be quite small, on the order

\(^1\)For clarity, the following terms are used to describe physical dimensions. Horizontal length: long/short. Horizontal width: wide/narrow. Vertical height: thick/thin.

\(^2\)As discussed later in Section 2.6, we assume pressure changes that are fractions of an atmosphere, so the diaphragm deflection is much less than the diaphragm thickness.

\(^3\)However, to increase sensitivity, the tests described in Section 4.5 were performed with source voltages around 20 V.
of microvolts. Therefore, in order to improve the signal-to-noise ratio of the sensor, we amplify the signal with a simple measurement chain: a pair of sensing wires attached to the bridge output of each sensor. Each pair of wires is fed into a set of off-wafer amplifying circuits for data analysis. Another scheme for amplification is a set of integrated single-stage differential amplifiers transistor circuits built into the wafer, one for each pressure sensor. This integrated circuit is discussed in Section 5.3.
2.2 Wafer-Level Design

The wafer-level features of the pressure sensor systems designed and fabricated for this thesis are described here. In all, five rounds of devices were developed to test various combinations of components of the sensor system described in Section 2.1.

1. Pressure-activated diaphragms without strain-gauge resistors;
2. Electrically isolated strain-gauge resistors on dummy wafers;
3. Electrically isolated strain-gauge resistors on pressure-activated diaphragms;
4. Fully interconnected strain-gauge sensors on pressure-activated diaphragms without amplifying transistors;
5. Fully interconnected strain-gauge sensors on pressure-activated diaphragms with amplifying transistors.

Rounds 1, 2, 3 and 4 have been fabricated and tested. Round 1 demonstrated the suitability of thin silicon diaphragms for sensing pressure. Round 2 showed that our resistor design can be reliably and repeatedly fabricated. Round 3 showed that the strain-gauge resistors can act as pressure sensors. Round 4 enabled the devices to be used underwater. Round 5, left as future work, will reduce the noise and enable $x$-$y$ addressing to allow for more efficient use of input and output wires by integrating amplifier and array read-out circuitry directly on the wafer.

2.2.1 Air channels

As discussed in Chapter 1, one of the challenges in designing the pressure sensor array is the equilibration of back pressure, which is pressure applied to the back-side of the diaphragms from within the sensor cavity. Since we are interested in detecting the small-signal pressure across the entire array, we increase our signal-to-noise by removing the large-signal pressure (DC component) via a common back pressure. We designed fluidic channels that enable the
back pressure to respond quickly to large-scale overall changes in pressure, such as those experienced when the entire system moves up or down relative to sea level.

Figure 2-3 shows a schematic of such a channel system. The sensor cavities are all connected to the long, snaking air channel, which opens to the ambient water. As the sensor array is lowered in water, the water pressure around the wafer increases, thus pushing water into the channel. As the air-water interface in the channel moves to a new equilibrium, the air pressure in the cavities and channel adjust to balance the increase in water pressure. Thus, the diaphragms, which measure the pressure difference between their local external environment and the common air pressure in the cavities, do not experience the large-signal pressure change. The channel is shaped with a constricted section such that the mechanics of air flow acts as a lowpass filter. The benefit of this filter is discussed in Section 2.9.

![Figure 2-3: Schematic of air channels for underwater sensors.](image)

### 2.2.2 Round 1

Round 1 devices are isolated diaphragms without strain-gauge resistors. Each wafer set consists of nine identical columns of diaphragms. Each column has ten diaphragms; two each of diaphragm sizes 1000 µm (1 mm), 1414 µm, 2000 µm, 2828 µm and 4000 µm. The overlay of the wafer-level features is presented in Figure 2-4. The air channels are etched in Pyrex and connect all the cavities in a column together. The nine columns of air cavities are isolated from one another.
2.2. WAFER-LEVEL DESIGN

The wafer is diced into isolated columns, and one diaphragm in each column is deliberately pierced. We interface the air channel to a syringe-controlled manometer\textsuperscript{4} via copper tubes glued to the broken cavity. The manometer manipulates and measures the back pressure, deflecting the diaphragm. Round 1 devices confirm that the deflection behavior of the diaphragm is sufficiently consistent and sensitive to act as the mechanical sensing component of the strain-gauge sensor.

2.2.3 Round 2

Round 2 simply consists of isolated strain-gauge resistors on dummy wafers. Each resistor has large probe pads on each end. The cell-by-cell layout corresponds to that of Round 1 and the resistor layout is presented in Figure 2-5. The inset shows a single cell of resistors and access pads for a 4 mm device. The design of the strain-gauge resistors is discussed in Section 2.7. The resistors are visually examined under a microscope and their resistances are measured.

\textsuperscript{4}The operation of the manometer is described in Section 4.2.
Figure 2-4: Overlay of Round 1 devices (actual size). The wafer is 150 mm in diameter. The air channels (blue) are etched in Pyrex and connect all the cavities in a column together. The bases of the cavities (red) are slightly wider than the diaphragms (black).
Figure 2-5: Layout of resistors from Rounds 2 and 3. The wafer is 150 mm. (Inset) Resistors and access pads of one 4 mm cell. The boundary of the diaphragm is dashed in red.
2.2.4 Round 3

Round 3 combines the first two rounds to build isolated strain-gauge resistors on pressure-activated diaphragms. Two classes of Round 3 devices are fabricated.\(^5\) Round 3a devices combines the resistor design of Round 2 (Figure 2-5) with the diaphragms and large air channels etched in Pyrex of Round 1 (Figure 2-4). Round 3b modifies the air channels to thin and narrow channels etched in silicon. The overlay of the wafer-level features is presented in Figure 2-6. The thin and narrow channels alternate sides of the column to reduce the risk of the silicon wafer from breaking. To further mitigate the risk, the silicon channels do not run to the silicon cavities. Instead, the small gap is bridged by slight square etches in Pyrex. Another improvement with Round 3b is the removal of the four sensors at the corners of the wafer. The reason for this minor change is explained at the end of Subsection 3.4.3.

The deflections of the diaphragms are manipulated as described in earlier for Round 1 by a manometer through a deliberately pierced cavity. Additionally, microscope probes are attached to the resistor probe pads to electrically access the sensor as pressure is applied from the back-side. Results from these experiments are discussed in Sections 4.3, 4.4 and 4.5.

\(^5\)In addition to the design of the air channels, the fabrication processes for the two classes differed as well. This is discussed in Section 3.2.
Figure 2-6: Overlay of Round 3b devices (actual size). The wafer is 150 mm in diameter. The air channels (red lines) are etched in silicon. The air channels are bridged to the cavity bases (red squares) by small etches in Pyrex (blue squares). The bases of the cavities (red squares) are slightly wider than the diaphragms (black).
2.2.5 Round 4

In this set of devices, the sensors are no longer isolated and are instead each wired up on-wafer in a Wheatstone bridge configuration. The sensors are powered and accessed via a custom-made Tech-Etch cable system (discussed later in Section 4.2) that electrically contacts the connection pads on the silicon wafer at one end. The wiring layout is shown in Figure D-13 in Appendix D.

Each Round 4 wafer consists of 24 sensors with 2000 μm square diaphragms, spaced by 2000 μm. The layout can be found in Figure D-12 in Appendix D.6

A single snaking air channel is etched into the Pyrex wafer to connect the cavities under all the diaphragms. Since the channel exits to the environment, water is free to flow into the channel but the channel is long enough that water cannot reach the cavities under the diaphragms. A constricted section in the channel lowpass filters the air flow. As the entire wafer is lowered or raised underwater, the water-air interface in the channel shifts accordingly, which removes the common large-signal change in pressure experienced by all the sensors. Thus, the pressure across each diaphragm remains within the range of the sensors and the sensors are sensitive only to small signal changes. 1 μm of Parylene polymer is added to the top layer of the wafer as a waterproofing material. The wafer is mounted onto a plastic holder for support and control of flow. The entire system can then be placed underwater to detect local changes in pressure.

Figure 2-7 shows the wafer-level layout for Round 4 devices. Preliminary tests on these devices are discussed in Section 4.6.

2.2.6 Round 5

The proposed wafer-level layout of the fully interconnected strain-gauge sensors on pressure-activated diaphragms with amplifying transistors is discussed in Section 5.3.

---

6Figure D-12 has three additional squares, which are dummy diaphragms without strain-gauge resistors.
Figure 2-7: Overlay of Round 4 devices (actual size). The wafer is 150 mm in diameter. The snaking air channel (blue) is etched in Pyrex and connect all the cavities together. The channel also has a constricted section that acts as a lowpass filter (narrow red line between large blue squares). The bases of the cavities (red) are slightly wider than the diaphragms (black). The 56 access pads (orange) are at the bottom. The Tech-Etch cable (outlined in red) is overlaid on those pads.
2.3 Properties of Silicon

The properties of silicon relevant for modeling device behavior and designing the fabrication process are described here. First, the standard Miller indices, which indicate the directions within a crystalline structure, are defined. Then, the elastic properties, namely Young’s modulus ($E_{ij}$), Poisson’s ratio ($\nu_{ij}$) and the shear modulus ($G_{ij}$), are listed.

2.3.1 Crystalline structure of silicon

Directions and planar orientations of silicon wafers are presented throughout this thesis using standard Miller indices. Directions within a silicon crystal are indicated in brackets $[xyz]$ as if specifying a vector, where $x$, $y$ and $z$ are the components along those lattice axes. Negative numbers are indicated with a bar above the absolute value. For example, $[01\overline{1}]$ represents the direction parallel to the vector $(0, 1, -1)$. Likewise, planes are specified using parentheses, where $(xyz)$ specifies the plane normal to the $[xyz]$ direction. Figure 2-8 illustrates three distinct pairs of directions and corresponding planes.

![Figure 2-8: Crystal planes and major directions. The shaded areas represent crystal planes and the vectors indicate crystal directions. Reproduced from [66].](image)

Because of the lattice symmetry, certain sets of directions or planes are equivalent. Angle and curly brackets denote such degenerate directions and planes, respectively. For example, the $[100]$, $[010]$ and $[001]$ directions are called $\langle 100 \rangle$ directions, and the $(100)$, $(010)$ and $(001)$ planes are called $\{100\}$ planes. The orientation of the silicon wafer with
respect to the crystal lattice affects the results of various wafer chemical processes as well as the mechanical properties of structures built from the wafer.

Wafers are identified by the plane of their top surface, or face. All silicon wafers described in this thesis are standard 150-mm diameter (100) wafers with wafer $x$, $y$ and $z$ coordinates\(^7\) along the [01\text{\overline{1}}], [011], and [100] directions of the crystal lattice, respectively, where $x$ is parallel to the wafer flat, $y$ is perpendicular to the wafer flat and in the plane of the wafer face, and $z$ is out of the wafer face (Figure 2-9).

![Crystal orientation in (100) silicon wafers showing (a) the direction normal to the surface, and (b) the directions of the wafer $x$ and $y$ axes. The wafer $x$ axis is parallel to the wafer flat. Reproduced and corrected from [45].](image)

**Figure 2-9:** Crystal orientation in (100) silicon wafers showing (a) the direction normal to the surface, and (b) the directions of the wafer $x$ and $y$ axes. The wafer $x$ axis is parallel to the wafer flat. Reproduced and corrected from [45].

### 2.3.2 The elastic properties of silicon

The behavior of the silicon-based pressure sensors is dependent on silicon’s elastic properties. Furthermore, as an anisotropic material, silicon’s Young’s modulus ($E_i$), Poission’s ratio ($\nu_i$) and shear modulus ($G_{ij}$) depend on its crystal orientation. For example, possible values of Young’s modulus range from 130 to 188 GPa, and those for Poisson’s ratio range from 0.048 to 0.40 [45]. These three elastic measures are related to the compliance matrix ($S$), which

\(^7\text{Note that there are two sets of axes named “x-y-z”: the crystal lattice and the wafer. The use of the same symbols is unfortunate, but common in microfabrication literature. Context should make the meaning clear.}\)
describes the relationship between strain\(^8\) \((\epsilon_{ij})\) and stress \((\sigma_{ij})\) in the form of Hooke’s law: 
\[\vec{\epsilon} = \mathbf{S} \vec{\sigma}.\]
Although a homogeneous, mechanically conservative\(^9\), but generally anisotropic material has at most 21 independent constants in its compliance matrix, symmetry can reduce this number. Due to its cubic structure, silicon exhibits orthotropic elastic properties, \(i.e.\) there exist three orthogonal axes where the shear and axial components of stress and strain are decoupled. Therefore, the orthotropic form of Hooke’s law is

\[
\begin{bmatrix}
\epsilon_{xx} \\
\epsilon_{yy} \\
\epsilon_{zz} \\
\epsilon_{yz} \\
\epsilon_{zx} \\
\epsilon_{xy}
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{E_x} & -\frac{\nu_{yx}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\
-\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0 \\
-\frac{\nu_{xz}}{E_x} & -\frac{\nu_{zy}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G_{zx}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}}
\end{bmatrix}
\begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{yz} \\
\sigma_{zx} \\
\sigma_{xy}
\end{bmatrix},
\] (2.1)

where the conservative property requires the compliance matrix to be symmetric:

\[
-\frac{\nu_{xy}}{E_x} = -\frac{\nu_{yx}}{E_y}, \quad -\frac{\nu_{xz}}{E_x} = -\frac{\nu_{zx}}{E_z}, \quad -\frac{\nu_{yz}}{E_y} = -\frac{\nu_{zy}}{E_z}.
\] (2.2)

Thus, orthotropic decoupling reduces the number of independent constants in \(\mathbf{S}\) from 21 to 9. For standard (100) silicon, the symmetry between the \(x\) and \(y\) axes, which are both along \(\langle 110 \rangle\) directions, further reduces the number of independent constants to 6 \cite{45}:

\[
E_x = E_y = 169 \text{ GPa}, \quad E_z = 130 \text{ GPa},
\] (2.3)

\[
\nu_{yz} = \nu_{xz} = 0.36, \quad \nu_{zx} = \nu_{zy} = 0.28, \quad \nu_{xy} = \nu_{yx} = 0.064,
\] (2.4)

\[
G_{yz} = G_{zx} = 79.6 \text{ GPa}, \quad G_{xy} = 50.9 \text{ GPa}.
\] (2.5)

\(^8\)In this thesis, the term shear strain refers strictly to pure shear strain, not engineering shear strain.

\(^9\)A material is mechanically conservative if the work done to strain it is independent of the physical path taken.

\(^{10}\)Although 7 values are listed here, the two values of \(\nu_{ij}\) involving the \(z\) direction, 0.36 and 0.28, are not independent of each other. They are related through the conservative property as described in Equations 2.2. To go further, a perfectly isotropic material, that is one whose mechanical properties are completely identical regardless of orientation, has only two independent elastic constants: the Young’s modulus \((E)\) and the Poisson’s ratio \((\nu)\). Its shear modulus is related to them by \(G = \frac{E}{2(1+\nu)}\).
2.3. PROPERTIES OF SILICON

Dopants typically alter silicon’s elastic properties by only up to 3%, so these effects can be safely ignored for most calculations [45]. However, dopants can cause internal stress, even if the bulk elastic properties do not change.

2.3.3 The elastic properties of thin silicon diaphragms

Since this thesis uses the elastic properties of silicon only in the context of thin silicon diaphragms of length $L$ in the wafer $x$ and $y$ directions (or the planar directions) and uniform thickness $H$ in the $z$ direction, the relationship between stress and strain on the top surface of the diaphragm given by Equation 2.1 can be further simplified as follows. As discussed later in Section 2.6, for small diaphragm deflections, the vertical shear strains $\epsilon_{yz}$ and $\epsilon_{zx}$, and the normal strain $\epsilon_{zz}$ (and the corresponding stresses $\sigma_{yz}$, $\sigma_{zx}$ and $\sigma_{zz}$) are negligible compared to the planar axial strains $\epsilon_{xx}$, $\epsilon_{yy}$ and $\epsilon_{xy}$ (and the corresponding stresses $\sigma_{xx}$, $\sigma_{yy}$ and $\sigma_{xy}$).\(^\text{11}\) With these assumptions, the planar axial components of strain in terms of the planar axial components of stress are

\[
\begin{align*}
\epsilon_x &= \frac{1}{E}(\sigma_x - \nu \sigma_y), \\
\epsilon_y &= \frac{1}{E}(\sigma_y - \nu \sigma_x), \\
\end{align*}
\]

and the planar axial stresses in terms of the planar axial strains are

\[
\begin{align*}
\sigma_x &= \frac{E}{1-\nu^2}(\epsilon_x + \nu \epsilon_y), \\
\sigma_y &= \frac{E}{1-\nu^2}(\epsilon_y + \nu \epsilon_x),
\end{align*}
\]

where some subscripts are dropped for notational simplicity:

\[
\begin{align*}
\epsilon_x &\equiv \epsilon_{xx}, & \epsilon_y &\equiv \epsilon_{yy}, & \sigma_x &\equiv \sigma_{xx}, & \sigma_y &\equiv \sigma_{yy}, \quad (2.10) \\
E &\equiv E_x = E_y = 169 \text{ GPa}, & \nu &\equiv \nu_{xy} = \nu_{yx} = 0.064. \quad (2.11)
\end{align*}
\]

\(^{11}\)Note that it is impossible for both $\epsilon_{zz}$ and $\sigma_{zz}$ to be exactly zero simultaneously or else Equation 2.1 would be over-constrained. For the purposes of this thesis, we will certainly assume $\sigma_{zz} = 0$, which is common in the literature [73, 84, 19].
These conventions are adopted in subsequent sections regarding (100) silicon.

The final set of material parameters for characterizing the behavior of the pressure sensor is the flexural rigidities $D_x$, $D_y$ and $D_0$ of a two-dimensional diaphragm with thickness $H$ made of (100) silicon:

$$D_x = \frac{E_x H^3}{12(1 - \nu_{xy} \nu_{yx})} = (14.1 \text{ GPa}) \times H^3,$$

$$D_y = \frac{E_y H^3}{12(1 - \nu_{xy} \nu_{yx})} = (14.1 \text{ GPa}) \times H^3,$$

$$D_0 = \frac{E_x \nu_{xy} H^3}{12(1 - \nu_{xy} \nu_{yx})} = (0.905 \text{ GPa}) \times H^3.$$

Likewise, the torsional rigidity is

$$D_{xy} = \frac{G_{xy} H^3}{12} = (4.24 \text{ GPa}) \times H^3.$$

(2.15)
2.4 Wheatstone Bridge Circuit

Since the changes in the resistances of the strain gauges are small, we implement a Wheatstone bridge circuit, a common method for detecting and measuring small changes in resistance. This configuration is used in both the piezoresistive pressure sensors described in Section 2.5 and the strain-gauge pressure sensors described in subsequent sections of this chapter. The output voltage of the Wheatstone bridge is analyzed below.

The Wheatstone bridge is defined by the configuration of four resistors, $R_1$, $R_2$, $R_3$ and $R_4$, as shown in Figure 2-10, where $V_s$ is the source voltage and $V_o$ is the measured output voltage.

![Figure 2-10: The Wheatstone bridge circuit.](image)

The ratio of output voltage to source voltage is

$$\frac{V_o}{V_s} = \frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4}$$

$$= \frac{R_1 R_3 - R_2 R_4}{(R_1 + R_2)(R_3 + R_4)}. \quad (2.16)$$

Changes in the resistances due to pressure-induced strain will thus lead to changes in $V_o$. In order to maximize the signal-to-noise ratio of $V_o$, we design a balanced bridge such that the unstrained output $V_{o,\text{unstrained}} = 0$, which occurs when $R_1 R_3 = R_2 R_4$. This is achieved by designing all four resistors to be of equal resistance, $R_0$, under no strain.

\[\text{As shown in Section 2.8, } \Delta R/R \text{ is on the order of parts per 100 million for each pascal of pressure change.}\]
Let $\alpha_i$ be the relative change in resistance, or $\Delta R_i/R_i$, upon strain. The resistances change to new values

$$R_{i,\text{new}} = (1 + \alpha_i)R_{i,\text{old}} \quad \forall i \in [1, 4]$$  \hspace{1cm} (2.18)

$$= (1 + \alpha_i)R_0.$$  \hspace{1cm} (2.19)

Substituting the new strained $R_i$ values into Equation 2.17, we see that $|V_o/V_s|$ is maximized when $\alpha_1$ and $\alpha_3$ have the same sign, and $\alpha_2$ and $\alpha_4$ also have the same sign, but opposite that of $\alpha_1$ and $\alpha_3$. We further choose diagonally opposite resistors to be identical so that $\alpha_1 = \alpha_3$ and $\alpha_2 = \alpha_4$. Then, the ratio of $V_o$ to $V_s$ is

$$\frac{V_o}{V_s} = \frac{(1 + \alpha_1)^2R_0^2 - (1 + \alpha_2)^2R_0^2}{(2 + \alpha_1 + \alpha_2)^2R_0^2}$$  \hspace{1cm} (2.20)

$$= \frac{(1 + \alpha_1 + 1 + \alpha_2)(1 + \alpha_1 - 1 - \alpha_2)}{(2 + \alpha_1 + \alpha_2)^2}$$  \hspace{1cm} (2.21)

$$= \frac{(2 + \alpha_1 + \alpha_2)(\alpha_1 - \alpha_2)}{(2 + \alpha_1 + \alpha_2)^2}$$  \hspace{1cm} (2.22)

$$\frac{V_o}{V_s} = \frac{\alpha_1 - \alpha_2}{2 + \alpha_1 + \alpha_2} \approx \frac{\alpha_1 - \alpha_2}{2},$$  \hspace{1cm} (2.23)

where the final approximation assumes $\alpha_i \ll 1$. Equation 2.23 is used later in Sections 2.5 and 2.8 to calculate the sensitivities of standard piezoresistive pressure sensors as well as our strain-gauge pressure sensors.

It can similarly be shown that when only $R_1$ and $R_2$ undergo relative changes $\alpha_1$ and $\alpha_2$, respectively, and $R_3$ and $R_4$ remain fixed at $R_0$, thus forming a half bridge, the ratio of $V_o$ to $V_s$ is

$$\left.\frac{V_o}{V_s}\right|_{\text{half}} = \frac{\alpha_1 - \alpha_2}{2(2 + \alpha_1 + \alpha_2)} \approx \frac{\alpha_1 - \alpha_2}{4},$$  \hspace{1cm} (2.24)

or half the sensitivity of the full bridge. Finally, when only a single resistor $R_1$ undergoes a relative change $\alpha_1$ and all the other resistors remain fixed at $R_0$, thus forming a quarter
2.4. WHEATSTONE BRIDGE CIRCUIT

bridge, the ratio of $V_o$ to $V_s$ is

$$\left| \frac{V_o}{V_s} \right|_{\text{quarter}} = \frac{\alpha_1}{2(2 + \alpha_1)} \approx \frac{\alpha_1}{4}. \quad (2.25)$$

Equation 2.25 is used later in Sections 4.4 and 4.5 when fabricated strain-gauge resistors are individually tested.
CHAPTER 2. DEVICE DESIGN

2.5 Piezoresistive Pressure Sensors

We first analyze a pressure sensor that operates according to the piezoresistive properties of silicon, a popular choice in commercial MEMS applications, to provide a basis of comparison with the strain-gauge sensor. Although piezoresistive pressure sensors generally have a higher sensitivity than strain-gauge pressure sensors do, underwater sensing applications prefer the strain-gauge technology for several reasons [53]. First, piezoresistive gauges are more sensitive to temperature change. In an uncontrolled macro-scale environment like the ocean, such sensors would be difficult to calibrate. Second, they require more complex fabrication steps, including doping. Third, metal strain-gauge resistors can endure a much greater elongation before fracture than piezoresistive silicon resistors, which enables their use in flexible polymer materials and provides mechanical robustness. Such polymers avoid the brittleness and high costs of silicon fabrication. Finally, strain-gauge polymers are easier to produce in the laboratory than piezoresistive polymers are.

The ratio of the change in resistance $\Delta R$ to the resistance $R$, called $\alpha$ in Section 2.4, of a resistor in a material with piezoresistive coefficients $\pi_i$ and stresses $\sigma_i$ is

$$\alpha = \frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t, \quad (2.26)$$

where the subscripts $l$ and $t$ distinguish the longitudinal and transverse stresses with respect to the resistor length axis.

For resistors arranged along a $\langle 110 \rangle$ direction on (100) silicon wafers, the piezoresistive coefficients are shown in Table 2.1. These figures assume low doping levels ($< 10^{17}$ cm$^{-3}$) and room temperature ($25^\circ$C). The piezoresistive coefficients decrease with increasing doping concentration and temperature.

<table>
<thead>
<tr>
<th>Type</th>
<th>$\pi_l$</th>
<th>$\pi_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-type</td>
<td>−31.2</td>
<td>−17.6</td>
</tr>
<tr>
<td>p-type</td>
<td>+71.8</td>
<td>−66.3</td>
</tr>
</tbody>
</table>

Table 2.1: Piezoresistive coefficients along a $\langle 110 \rangle$ direction for both types of doped silicon. The units are $10^{-11}$ Pa$^{-1}$ [73, p. 474].
Consider Figure 2-11, which shows the placement of four resistors along a (110) direction at the centers of the four edges of the surface of a square diaphragm with edge length \( L \) and thickness \( H \).

When a pressure \( P \) is applied from above the diaphragm, the diaphragm experiences stress and strain. As shown in [19] by finite-element methods (FEM), the stress (and strain) on the diaphragm is highest at the center of the edge, which we will call location CE, in the direction perpendicular to the edge:

\[
\sigma_{\perp,\text{CE,FEM}} = 0.294 \left( \frac{L}{H} \right)^2 P. \tag{2.27}
\]

From Equations 2.6 and 2.7, the strain in the parallel direction is

\[
\epsilon_{\parallel} = \frac{1}{E} (\sigma_{\parallel} - \nu \sigma_{\perp}). \tag{2.28}
\]

Because the four edges are fixed, there is no strain in the direction parallel to an edge anywhere along the edge, \( i.e. \epsilon_{\parallel,\text{edge}} = 0 \). Thus, the stress at the center of an edge in the
CHAPTER 2. DEVICE DESIGN

direction parallel to the edge is

\[ \sigma_{\parallel, \text{CE,FEM}} = \nu \sigma_{\perp, \text{CE,FEM}} \]
\[ = 0.064 \times 0.294 \left( \frac{L}{H} \right)^2 \text{P} \]
\[ = 0.019 \left( \frac{L}{H} \right)^2 \text{P}. \]

For typical dimensions \( L = 2000 \mu \text{m} \) and \( H = 20 \mu \text{m} \), this produces

\[ \sigma_{\perp, \text{CE,FEM}} = 2940 \text{P}, \quad \text{(2.32)} \]
\[ \sigma_{\parallel, \text{CE,FEM}} = 190 \text{P}. \quad \text{(2.33)} \]

Since \( \sigma_{\perp, \text{CE,FEM}} \) is more than 15 times \( \sigma_{\parallel, \text{CE,FEM}} \), one of the terms in Equation 2.26 dominates the other, which helps us choose the optimal type of silicon in which to build piezoresistors. The absolute values of \( \pi_l \) and \( \pi_t \) for p-type silicon are larger than those for n-type silicon, which implies more sensitivity to stress. Additionally, the coefficients for the two orthogonal directions in p-type silicon have opposing signs, which is appropriate for the Wheatstone bridge described earlier. Thus, we choose p-type silicon as the substrate for the piezoresistive pressure sensor.

We use Equations 2.32 and 2.33 and Table 2.1 to calculate the relative resistance change \( \alpha \) in Equation 2.26 for the four resistors. For \( R_1 \) and \( R_3 \), where the longitudinal direction of the resistors is perpendicular to the diaphragm edge, the change is

\[ \alpha_1 = \pi_l \sigma_{\perp, \text{CE,FEM}} + \pi_t \sigma_{\parallel, \text{CE,FEM}} \]
\[ = (71.8 \times 10^{-11} \text{Pa}^{-1})(2940 \text{P}) + (-66.3 \times 10^{-11} \text{Pa}^{-1})(190 \text{P}) \]
\[ = (1.98 \times 10^{-6} \text{Pa}^{-1}) \text{P}. \]

Similarly, the relative change in resistance for \( R_2 \) and \( R_4 \) is found by reversing the transverse
and longitudinal stresses:

\[ \alpha_2 = \pi l \sigma_{\parallel,CE,FEM} + \pi t \sigma_{\perp,CE,FEM} \]  
(2.37)

\[ = (71.8 \times 10^{-11} \text{ Pa}^{-1})(190P) + (-66.3 \times 10^{-11} \text{ Pa}^{-1})(2940P) \]  
(2.38)

\[ = (-1.81 \times 10^{-6} \text{ Pa}^{-1})P. \]  
(2.39)

Applying these values to the relationship between the output voltage and source voltage of a Wheatstone bridge, shown in Equation 2.23, with the assumption that \( P \ll 10^6 \text{ Pa} \), we obtain

\[ \frac{V_o}{V_s} \approx (1.90 \times 10^{-6} \text{ Pa}^{-1})P. \]  
(2.40)

For a typical source voltage of 10 V, this corresponds to a sensitivity of 19.0 \( \mu \text{V/Pa} \).
2.6 Mechanical Model of the Diaphragm

Now that piezoresistive pressure sensors have been studied, let us move on to strain-gauge resistors. First, we develop a mechanical model of the diaphragms that form the basis of the strain-gauge pressure sensors. This includes understanding the deflection of the diaphragm and the strains on the diaphragm surface as pressure is applied. Later, in Section 2.7, we show how this information aids in optimizing the design of the strain-gauge resistors.

2.6.1 Diaphragm assumptions

We begin by assuming the mechanical behavior of the diaphragm is dominated by the silicon layer as it is far thicker than the other materials deposited or bonded to it. Next, to model the behavior of the diaphragm, we use the linear, elastic, small-deflection theory of bending for thin plates\footnote{There is a subtle, but important, distinction between the terms “plate” and “diaphragm”. A plate is an ideal mathematical construct, whereas a diaphragm is a realized physical structure. Thus, we are modeling the silicon diaphragm as a plate.}, called Kirchhoff-Love plate theory, which assumes the following:

1. The material of the plate is elastic and homogeneous (though not necessarily isotropic\footnote{The material used in this thesis, silicon, is orthotropic.}).

2. The plate is initially flat at zero applied pressure.

3. The normal deflection of the plate is small compared to the thickness of the plate, which in turn is small compared to the length and width of the plate. Thus, the slope of the deflected surface is very small.

4. The thickness of the plate does not change during deformation.

5. The middle surface of the plate, which is halfway between and parallel to the top and bottom plate surfaces, remains unstrained and unstressed during deformation.

6. The vertical shear strains and the normal strain (and the corresponding stresses) are negligible compared to the planar strains (and the corresponding stresses).

Furthermore, we assume that the plate is clamped on all four sides. However, in reality, silicon cannot be ideally clamped [25].
2.6. MECHANICAL MODEL OF THE DIAPHRAGM

2.6.2 Governing equations

Let a thin square silicon plate of side length $L$ and thickness $H$ be subjected to an applied uniform pressure $P(t)$ from above, which in general is a function of time $t$. Let $w(x, y, t)$ represent the normal deflection of the square plate as a function of its horizontal $x$ and $y$ coordinates, where the origin is the center of the plate, and time $t$, in response to the applied pressure. By convention, the positive $w$ direction is downward. Figure 2-12 depicts this scenario.

\[ \frac{\partial^2}{\partial x^2} M_x + \frac{\partial^2}{\partial y^2} M_y + \frac{\partial^2}{\partial x \partial y} M_{xy} + N'_x \frac{\partial^2}{\partial x^2} w + N'_y \frac{\partial^2}{\partial y^2} w = -P(t) - \rho \frac{\partial^2}{\partial t^2} w, \quad (2.41) \]

where $\rho$ is the mass of the plate per unit area and $N'_x$ and $N'_y$ are the in-plane tensions per unit width in the $x$ and $y$ directions, respectively [19, 73]. The bending moments are

Figure 2-12: A square diaphragm of length $L$ and thickness $H$ subjected to an applied uniform pressure $P(t)$ from above; $w(x, y, t)$ is the normal deflection of the plate.
related to the deflection by the set of equations

\[ M_x = - \left[ D_x \frac{\partial^2}{\partial x^2} w + D_0 \frac{\partial^2}{\partial y^2} w \right], \quad (2.42) \]
\[ M_y = - \left[ D_y \frac{\partial^2}{\partial y^2} w + D_0 \frac{\partial^2}{\partial x^2} w \right], \quad (2.43) \]
\[ M_{xy} = 2D_{xy} \frac{\partial^2}{\partial x \partial y} w, \quad (2.44) \]

where the rigidities \( D_x = D_y, D_0 \) and \( D_{xy} \) were calculated on Page 56 in Section 2.3.

We assume the plate has no residual biaxial tensile stress, so \( N'_x = N'_y = 0 \).

Furthermore, as shown later in Section 2.9, the lowest resonant frequency of a diaphragm with \( L = 2000 \mu m \) and \( H = 20 \mu m \) is 71 kHz, and we assume changes in pressure are much slower than this frequency. Thus, we assume a quasi-static regime where \( P \) is constant and \( w \) is simply a function of \( x, y \) and \( P \).

Substituting Equations 2.42–2.44 into Equation 2.41, and dropping in-plane tension and time-dependent terms, we get the following governing equation for the normal deflection \( w(x, y) \):

\[ D_x \left[ \frac{\partial^4}{\partial x^4} w + 2\theta \frac{\partial^4}{\partial x^2 \partial y^2} w + \frac{\partial^4}{\partial y^4} w \right] = P, \quad (2.45) \]

where

\[ \theta \equiv \frac{D_0 + 2D_{xy}}{D_x}. \quad (2.46) \]

\( \theta \) can be interpreted as a measure of the isotropy of the elasticity of the material in the plane of the plate. For (100) silicon where the \( x-y \) coordinates are along the \( \langle 110 \rangle \) directions, \( \theta = 0.666 \). Note that this 90° rotational symmetry about the axis normal to the plate surface is not the same as perfect planar isotropy \( (\theta = 1) \), where material rotation by any angle about the \( z \) axis results in no difference in mechanical behavior.\(^{16} \) Note also that

\(^{15}\) If, instead, the diaphragm were dominated by the residual stress, it would be a membrane.

\(^{16}\) If the material is already orthotropic, this additional planar isotropic property would make it transverse orthotropic.
instead of using a shear modulus of $G_{xy} = 50.9$ GPa [45], some previous work [6, 19, 7] use $G_{xy} = 62.2$ GPa, which corresponds to $\theta = 0.798$.

The boundary conditions at the edges are

$$w \left( x = \pm \frac{L}{2} \text{ or } y = \pm \frac{L}{2} \right) = 0, \quad \frac{\partial}{\partial x}w \left( x = \pm \frac{L}{2} \right) = \frac{\partial}{\partial y}w \left( y = \pm \frac{L}{2} \right) = 0. \quad (2.47)$$

Although ideally clamped edges (expressed as the second boundary condition) are not physically possible, this effect is only influential near the edges.

### 2.6.3 The nature of the deflection function

While the normal deflection $w$, and by extension, the stress and strain, for circular plates are known in closed form, analytic solutions to Equation 2.45 with boundary conditions Equation 2.47 do not exist for rectangular diaphragms. Various quasi-analytical and numerical analyses have been performed [73, 84, 26, 3, 65, 6, 7, 19, 68]. Generally, $w$ is in the form of an infinite series of raised cosine terms [26, 84]. The first-order term sufficiently models the diaphragm deflection for the purposes of this thesis. Following [73], $w$ can be approximated as a function of the form

$$w(x, y) = \frac{c_{1}}{4} \left[ 1 + \cos \left( \frac{2\pi x}{L} \right) \right] \left[ 1 + \cos \left( \frac{2\pi y}{L} \right) \right], \quad (2.48)$$

where the origin is the center of the plate and $c_{1}$ is the deflection at the center of the plate, which is where the deflection is greatest.\textsuperscript{17}

While previous work has focused on reducing the square errors between the modeled and experimental deflections, little work has been done on accurately modeling the stress and strain on the surface of the diaphragm. Since these quantities depend on the second spatial derivatives of the deflection function instead of the deflection itself, accurately modeling the deflection function may not necessarily improve the spatial derivatives. Furthermore, any discrepancies produced by these models would be masked by other simplifications to our

---

\textsuperscript{17}The subscript in $c_{1}$ refers to the fact that it is the amplitude of the first mode of vibration for the diaphragm. This thesis does not discuss other modes, but the notation is used for consistency with other works.
diaphragm model, including ignoring the effects of multiple materials on the diaphragm, variations in the diaphragm thickness, residual stress and material imperfections in the strain-gauge resistors, such as fractures and holes. These effects are discussed in Sections 4.3 and 4.5.

2.6.4 Deflection as a function of pressure

In general, the relationship between applied pressure $P$ and the deflection at the center of the plate $c_1$ is given by the following three-term equation:

$$
P = \left\{ C_r \left[ \frac{\sigma_0 H}{L^2} \right] + C_b \left[ \frac{E H^3}{(1-\nu^2)L^4} \right] \right\} c_1 + C_s f_s(\nu) \left[ \frac{E H}{(1-\nu)L^4} \right] c_1^3, \quad (2.49)$$

where $C_r$, $C_b$ and $C_s$ are constants, $\sigma_0$ is residual stress in the diaphragm, and $f_s(\nu)$ is a function of $\nu$ [73]. The first term, linear in $c_1$, is due to residual stress, which we assume is nonexistent in our devices. The second term, also linear, is due to bending. Finally, the third term, a cubic, is due to stretching. When the maximum deflection is less than the plate thickness, we can assume a model where there is no stretching. Thus, the pressure-deflection model relationship is:

$$
P = C_b \left[ \frac{E H^3}{(1-\nu^2)L^4} \right] c_1. \quad (2.50)$$

Writing $c_1$ in terms of $P$ and defining the constant $K_E \equiv 1/C_b$, we get:

$$
c_1 = K_E \left[ \frac{(1-\nu^2)L^4}{E H^3} \right] P. \quad (2.51)$$

In the literature, the deflection-pressure relationship is often written in terms of the flexural rigidity $D_x = \frac{E H^3}{12(1-\nu^2)}$:

$$
c_1 = K_D \left[ \frac{L^4}{D_x} \right] P, \quad (2.52)$$
where the two constants are related by

\[ K_D = \frac{K_E}{12}. \]  

(2.53)

The value of \( K_D \) for anisotropic (100) silicon with coordinates along the \((110)\) directions has been measured by several groups. \([6]\) and \([7]\) separately obtained the value \( K_D = 0.00133 \) using different methods.\(^{18}\) \([19]\) obtained \( K_D = 0.001638 \) using finite-element analysis. In light of the fact that the \( K_D = 0.00133 \) value was published eight years after the \( K_D = 0.001638 \) value, and by two separate groups employing different techniques, this thesis uses \( K_D = 0.00133 \). As noted earlier, all of these sources use a slightly different value for the shear modulus \( G_{xy} \) than is generally accepted. Isotropic materials, on the other hand, have a well-known \( K_D = 0.00126 \) \([84, 26, 3, 65]\). For simplicity sake, some researchers use this value even for anisotropic silicon.

For \( K_D = 0.00133, \nu = 0.064, E = 169 \text{ GPa}, L = 2000 \mu\text{m}, H = 20 \mu\text{m}, \) the center deflection to pressure ratio is

\[ \frac{c_1}{P} = 0.188 \text{ nm}/\text{Pa}. \]  

(2.54)

Thus, one atmosphere (101.3 kPa) of pressure produces a center deflection of 19 \( \mu\text{m} \). Since the maximum pressure applied to the sensors is on the order of a few percent of an atmosphere, the deflection is much less than the diaphragm thickness \( H \), which satisfies one of the conditions of Kirchhoff-Love plate theory. We will set a conservative limit for deflection to be 10% of the diaphragm thickness. For a 2000 \( \mu\text{m} \) diaphragm, this corresponds to a maximum applied pressure of 10.6 kPa.

Measurements of the deflection-pressure relationship for various fabricated diaphragms are presented in Section 4.3.

\(^{18}\)\([6]\) models the deflection \( w \) with an infinite series of sinusoids and hyperbolic functions, whereas \([7]\) uses an infinite polynomial.
2.6.5 Strain as a function of pressure

We seek to calculate the strain experienced by the diaphragm due to deflection by pressure. The $x$- and $y$-components of strain on the top surface of the diaphragm are

$$
\varepsilon_x(x, y) = \frac{H}{2} \frac{\partial^2}{\partial x^2} w(x, y),
$$

(2.55)

$$
\varepsilon_y(x, y) = \frac{H}{2} \frac{\partial^2}{\partial y^2} w(x, y).
$$

(2.56)

Since shear strain merely translates the infinitesimal parallel resistors that make up a local section of a resistor relative to one another without changing their lengths or widths, it does not affect the resistance of strain-gauge resistors bound to the diaphragm surface. Thus, shear strain is omitted. As first described on Page 67, we use the following to model deflection $w$ as a function of the center deflection $c_1$:

$$
w(x, y, c_1) = \frac{c_1}{4} \left[ 1 + \cos \left( \frac{2\pi x}{L} \right) \right] \left[ 1 + \cos \left( \frac{2\pi y}{L} \right) \right].
$$

(2.57)

The second derivative of $w$ with respect to $x$ is

$$
\frac{\partial^2}{\partial x^2} w = \frac{\partial}{\partial x} \left( \frac{\partial}{\partial x} \left( \frac{c_1}{4} \left[ 1 + \cos \left( \frac{2\pi x}{L} \right) \right] \left[ 1 + \cos \left( \frac{2\pi y}{L} \right) \right] \right) \right)
$$

(2.58)

$$
= \frac{c_1}{4} \frac{\partial}{\partial x} \left[ -\frac{2\pi}{L} \sin \left( \frac{2\pi x}{L} \right) \right] \left[ 1 + \cos \left( \frac{2\pi y}{L} \right) \right]
$$

(2.59)

$$
= -\frac{c_1}{4} \left( \frac{2\pi}{L} \right)^2 \cos \left( \frac{2\pi x}{L} \right) \left[ 1 + \cos \left( \frac{2\pi y}{L} \right) \right]
$$

(2.60)

$$
\frac{\partial^2}{\partial x^2} w = -c_1 \left( \frac{\pi}{L} \right)^2 \cos \left( \frac{2\pi x}{L} \right) \left[ 1 + \cos \left( \frac{2\pi y}{L} \right) \right].
$$

(2.61)

Thus, the $x$-component of strain is

$$
\varepsilon_x(x, y, c_1) = -c_1 \frac{H}{2} \left( \frac{\pi}{L} \right)^2 \cos \left( \frac{2\pi x}{L} \right) \left[ 1 + \cos \left( \frac{2\pi y}{L} \right) \right].
$$

(2.62)
2.6. MECHANICAL MODEL OF THE DIAPHRAGM

Substituting the relationship between pressure $P$ and the center deflection $c_1$ from Equation 2.51, we obtain the $x$-component of strain as a function of pressure:

$$
\epsilon_x(x, y, P) = -K_E \frac{\pi^2}{2} (1 - \nu^2) \left( \frac{L}{H} \right)^2 \left( \frac{P}{E} \right) \cos \left( \frac{2\pi x}{L} \right) \left[ 1 + \cos \left( \frac{2\pi y}{L} \right) \right].
$$

(2.63)

By symmetry, the $y$-component of strain is

$$
\epsilon_y(x, y, P) = -K_E \frac{\pi^2}{2} (1 - \nu^2) \left( \frac{L}{H} \right)^2 \left( \frac{P}{E} \right) \left[ 1 + \cos \left( \frac{2\pi x}{L} \right) \right] \cos \left( \frac{2\pi y}{L} \right).
$$

(2.64)

Equations 2.63 and 2.64 are used to design strain-gauge resistors, as shown in Section 2.7.

2.6.6 Stress as a function of pressure

By substituting the expressions for strain from Equations 2.63 and 2.64 into the expressions for stress in terms of strain from Equations 2.8 and 2.9, we obtain the components of stress on the surface of the diaphragm as functions of pressure:

$$
\sigma_x(x, y, P) = -K_E \frac{\pi^2}{2} \left( \frac{L}{H} \right)^2 P \left\{ \cos \left( \frac{2\pi x}{L} \right) \left[ 1 + \cos \left( \frac{2\pi y}{L} \right) \right] + 
\nu \left[ 1 + \cos \left( \frac{2\pi x}{L} \right) \right] \cos \left( \frac{2\pi y}{L} \right) \right\}.
$$

(2.65)

$$
\sigma_y(x, y, P) = -K_E \frac{\pi^2}{2} \left( \frac{L}{H} \right)^2 P \left\{ \left[ 1 + \cos \left( \frac{2\pi x}{L} \right) \right] \cos \left( \frac{2\pi y}{L} \right) + 
\nu \cos \left( \frac{2\pi x}{L} \right) \left[ 1 + \cos \left( \frac{2\pi y}{L} \right) \right] \right\}.
$$

(2.66)

Setting the perpendicular and parallel directions to an edge of the diaphragm as $x$ and $y$, respectively, we choose to calculate the perpendicular stress at the center of an edge $(x, y) = (L/2, 0)$, which we called location CE. Evaluating the stress expression in Equation 2.65 at this location with $K_E = 12 \times K_D = 12 \times 0.00133$, the cosine model produces the following perpendicular stress:

$$
\sigma_{\perp, CE, \cos} = 0.158 \left( \frac{L}{H} \right)^2 P.
$$

(2.67)
Recall Equation 2.27 in the discussion about piezoresistive pressure sensors (Section 2.5), the perpendicular stress at the center of the edge was calculated by finite-element methods (FEM) by [19] to be

\[
\sigma_{\perp,\text{CE,FEM}} = 0.294 \left( \frac{L}{H} \right)^2 P. \tag{2.68}
\]

The discrepancy between Equations 2.67 and 2.68 is from the use of the raised cosine model to approximate the deflection in the former.

However, the stress at the center of the diaphragm is in better agreement across sources. According to [19], the stress (in both \(x\) and \(y\) directions) at the center of a (100) silicon diaphragm is

\[
\sigma_{(0,0),\text{FEM}} = -0.134 \left( \frac{L}{H} \right)^2 P. \tag{2.69}
\]

The stress model in Equation 2.65 with \(K_E = 12 \times K_D = 12 \times 0.00133\) produces

\[
\sigma_{(0,0),\text{cos}} = -0.168 \left( \frac{L}{H} \right)^2 P. \tag{2.70}
\]
2.7 Strain-Gauge Resistors

The design of the four strain-gauge resistors, the sensing element of the devices, is explained below. Clearly, to maximize the sensitivity, the resistors should be concentrated at the high-strain points. However, the conduction lines that connect the Wheatstone bridge to the source voltage $V_s$ have non-negligible resistances, as they have lengths on the centimeter scale. In order to reduce the relative voltage drop on these conduction lines and maximize $V_s$ of the Wheatstone bridge, we increase the strain-gauge resistances, which entails occupying other, less sensitive, areas of the diaphragm surface with parts of the strain gauges. The gains in boosting the effective source voltage powering the bridge outweigh the losses in overall relative change in strain-gauge resistances. To increase the resistances of the strain gauges, we maximize the length of the resistors and minimize the cross-sectional area. Over an $L \times L$ square diaphragm, a snaking line resistor of width $L/n$ increases the total length by $\sim n$ while reducing the cross-sectional area by another $\sim n$, resulting in an $\sim n^2$ increase in resistance. Thus it is ideal to have closely spaced, narrow snaking lines of resistance across the entire diaphragm to maximize the resistance. This minimum width and spacing between lines is limited by the resolution of photolithography, which is discussed in Section 3.3.

2.7.1 Relative change in resistance of an infinitesimally small resistor

Consider an infinitesimally small metal resistor $dR$ bonded to the top surface of the silicon diaphragm. Under deformation by the diaphragm, the $x$- and $y$-components of strain are transferred to the resistor. We assume that the vertical height of the resistor is far thinner than the diaphragm, so it does not contribute to the deformation mechanics as analyzed earlier. For small strains, as assumed by Kirchhoff-Love plate theory, the relative change in resistance as a result of diaphragm deformation is

$$\alpha_{dR} = \frac{\Delta dR}{dR} = \epsilon_l - \epsilon_w - \epsilon_h,$$  \hspace{1cm} (2.71)
where \( l, w \) and \( h \) are the components of strain experienced by the resistor along its length, width and height, respectively.\(^{19}\) The strains along the length and width of the resistor are set by the two-dimensional strains of the diaphragm, depending on orientation, and the strain along the height is related to the other two as

\[
\epsilon_h = \frac{-\nu_R}{1 - \nu_R} (\epsilon_l + \epsilon_w), \quad (2.72)
\]

where \( \nu_R \) is the isotropic Poisson’s ratio of the resistor material. Thus, the relative change in resistance in terms of the surface strains is

\[
\alpha_{dR} = \Delta \frac{dR}{dR} = \epsilon_l - \epsilon_w - \frac{-\nu_R}{1 - \nu_R} (\epsilon_l + \epsilon_w) \quad (2.73)
\]

\[
= \frac{1}{1 - \nu_R} \epsilon_l + \frac{2\nu_R - 1}{1 - \nu_R} \epsilon_w. \quad (2.74)
\]

### 2.7.2 Simulating resistance change

For a real resistor of resistance \( R \), the overall relative change is the weighted average relative change of its infinitesimal components, integrating lengthwise:

\[
\alpha = \frac{1}{R} \int \alpha_{dR} dR \quad (2.75)
\]

\[
= \frac{1}{R} \int_s \alpha_{dR}(s) \frac{\rho}{A(s)} ds, \quad (2.76)
\]

where \( s \) is the distance along the length of the resistor, \( \rho \) is the resistivity and \( A(s) \) is the cross-sectional area as a function of \( s \).

To simplify the resistor design, we constrain the resistor shape so that it consists of piecewise linear components whose lengths and widths are along the \( x \) and \( y \) diaphragm axes. Given these constraints, a MATLAB simulation, `resistor_design.m`, was written to aid resistor design according to the model described above. The expressions for the

\(^{19}\) Increases in length increase the resistance, whereas decreases in the cross-sectional area (width and height) increase the resistance.
components of strain as functions of pressure, described in Equations 2.63 and 2.64, were also used in the simulation. The code is given in Appendix F.

The simulation produces three graphs:

- The strain of the top surface of the diaphragm in the $x$ direction ($\epsilon_x$) as a function of normalized positions, $\tilde{x} = x/L$ and $\tilde{y} = y/L$.

- The local optimal resistor lengthwise orientation for maximizing resistance change.

- The sign of the resistance change when a local resistor is placed in the optimal direction.

Figure 2-13: The strain of the top surface of the diaphragm in the $x$ direction ($\epsilon_x$) as a function of normalized positions.

Several observations can be made from the results of the simulation. Figure 2-13 shows the strain of the top surface of the diaphragm in the $x$ direction ($\epsilon_x$) as a function of normalized positions. By symmetry, the strain in the $y$ direction ($\epsilon_y$) is obtained by reversing...
CHAPTER 2. DEVICE DESIGN

Figure 2-14: The local optimal resistor lengthwise orientation for maximizing resistance change. Green indicates areas where the $x$ direction is preferred over the $y$ direction, red indicates the opposite, and blue indicates area where neither direction is preferred.

the $x$ and $y$ axes. As noted earlier, the strain is highest at the center of the edge; i.e., $\epsilon_x$ is maximum at the points $(x, y) = (\pm L/2, 0)$. The strain reaches a minimum at the center of the diaphragm. Since these are all points where the absolute strain is relatively high, resistance should be concentrated near these locations.

Figure 2-14 shows the local optimal lengthwise direction for resistor placement. The resistance changes for both $x$ and $y$ orientations were calculated, and the one with the higher absolute value was selected. Green indicates areas where the $x$ direction is preferred over the $y$ direction, red indicates the opposite, and blue indicates area where neither direction is preferred. By symmetry, the diagonals $y = \pm x$ are blue. Since all the functions are continuous, all boundaries between the green and red regions should be blue; the discrete nature of the simulation inevitably causes such points to be skipped over.

Figure 2-15 shows the sign of the resistance change when a local resistor is placed in the
Figure 2-15: The sign of the resistance change when a local resistor is placed in the optimal direction. Magenta indicates a positive change; yellow indicates a negative change.
optimal direction as suggested by Figure 2-14. Magenta indicates a positive change; yellow indicates a negative change. This figure neatly divides the diaphragm into two regions: a center area where the resistors oriented optimally would change positively, and a larger ring area where the resistors oriented optimally would change opposingly. According to the principle of the Wheatstone bridge as described in Section 2.4, we place two resistors in one of these regions and two in the other.

2.7.3 Strain-gauge resistor pattern

Combining the insights from Figures 2-13, 2-14 and 2-15, we design four strain-gauge resistors on a square diaphragm in the pattern shown in Figure 2-16. The design exhibits odd symmetry about the center of the diaphragm, i.e. rotating it $180^\circ$ yields an identical pattern. The two resistors arranged in the center region change in the opposing direction as the two resistors arranged closer to the edges of the diaphragm. All four resistors have narrower lines (10 $\mu$m for a 2000 $\mu$m diaphragm), which yields higher resistances, near the previously mentioned areas where absolute strain is high, and wider lines (20 $\mu$m) elsewhere.

For the Round 3 devices, which include diaphragms with lengths ranging from 1000 $\mu$m to 4000 $\mu$m, the resistor dimensions are scaled accordingly. Since the ratios of lengths to widths remains constant, the resistance is scale-invariant.

This novel snaking resistor design is unnecessary for most MEMS strain-gauge pressure sensors, which concentrate resistance on the high-strain regions of the diaphragm because the devices do not have wafer-scale conduction lines, but the additional resistance here more than compensates for the loss in sensitivity.
Figure 2-16: The design of four strain-gauge resistors on a square diaphragm. The red line indicates the boundaries of the diaphragm (nominally 2000 \( \mu \text{m} \)).
2.8 Sensitivity

We estimate the maximum sensitivity of the strain-gauge pressure sensor, which, given the voltage noise level, provides the pressure resolution. Suppose the resistors were concentrated at the center of the edges of the diaphragm (locations CE), like those in the piezoresistive pressure sensors discussed in Section 2.5 were. We calculate the strains using Equations 2.32 and 2.33 and diaphragm parameters $L = 2000 \, \mu\text{m}$, $H = 20 \, \mu\text{m}$, $E = 169 \, \text{GPa}$ and $\nu = 0.064$:

\begin{align*}
\epsilon_{\perp,\text{CE}} &= \frac{1}{E} (\sigma_{\perp,\text{CE}} - \nu \sigma_{\parallel,\text{CE}}) = (1.73 \times 10^{-8} \, \text{Pa}^{-1}) P, \quad (2.77) \\
\epsilon_{\parallel,\text{CE}} &= 0. \quad (2.78)
\end{align*}

Thus, according to Equation 2.74, the relative changes in resistance for the resistors with lengths oriented perpendicular and parallel to the diaphragm edge are

\begin{align*}
\alpha_{\perp} &= (2.19 \times 10^{-8} \, \text{Pa}^{-1}) P, \quad (2.79) \\
\alpha_{\parallel} &= (-1.27 \times 10^{-8} \, \text{Pa}^{-1}) P, \quad (2.80)
\end{align*}

respectively, where a resistor Poisson’s ratio of $\nu_R = 0.21$ is assumed.\textsuperscript{20} Applying these values to the relationship between the output voltage and source voltage of a Wheatstone bridge, shown in Equation 2.23 with $\alpha_1 = \alpha_{\perp}$ and $\alpha_2 = \alpha_{\parallel}$, we obtain

\begin{equation}
\frac{V_o}{V_s} \approx (1.73 \times 10^{-8} \, \text{Pa}^{-1}) P, \quad (2.81)
\end{equation}

where we again assumed $P \ll 10^6 \, \text{Pa}$. For a typical source voltage of 10 V, this corresponds to a sensitivity of $0.173 \, \mu\text{V}/\text{Pa}$ for resistors concentrated at the edge centers. The use of less sensitive areas of the diaphragm reduces the sensitivity of the strain-gauge pressure sensors by a factor of approximately 2, or down to $0.087 \, \mu\text{V}/\text{Pa}$, which is much less sensitive than the $19.0 \, \mu\text{V}/\text{Pa}$ for the piezoresistive pressure sensor analyzed in Section 2.5.

\textsuperscript{20}This is the Poisson’s ratio of chromium, which was the primary material used to fabricate resistors for this thesis.
Thermal noise voltage is on the order of

\[ V_N \approx \sqrt{4kTRf}, \]  

(2.82)

where \( k \) is Boltzmann’s constant, \( T \) is temperature, \( R \) is resistance, and \( f \) is the frequency. Thus, for \( T = 300 \text{ K} \), \( R = 10 \text{ k}\Omega \), and a filtered bandwidth of \( f = 100 \text{ Hz} \), the thermal noise voltage is approximately 0.13 \( \mu \text{V} \). Therefore, the pressure resolution is on the order of 1.5 Pa. As discussed earlier in Chapter 1, object detection and identification requires only 10 Pa resolution, so the strain-gauge pressure sensor is sufficiently sensitive for undersea applications.
2.9 Dynamics

Estimates of the dynamics of the pressure sensor system are shown below. As a first pass, the resonant frequency, or the frequency of the lowest mode of vibration, of the diaphragm can be estimated by modeling the diaphragm as an ideal mass-spring system. We shall consider the oscillatory behavior of an infinitesimal square portion of the diaphragm of size $dL \times dL$ at the center of the diaphragm.

The system mass is best modeled as the total displaced mass. Strictly speaking, this mass is the sum of the mass of the diaphragm plus the mass of the water displaced by the flexing of the diaphragm. However, since the diaphragm is much thicker (20 $\mu$m) than the maximum vertical displacement of water\(^{21}\) and silicon is denser than water, the mass of the displaced water is negligible. The mass is the density of silicon times the volume of the diaphragm:

$$dm = \rho dV$$  \hfill (2.83)

$$= 2.3290 \text{ g/cm}^3 \times 20 \mu\text{m} \times dL^2$$  \hfill (2.84)

$$= 0.0469 \text{ kg/m}^2 \times dL^2.$$  \hfill (2.85)

According to Hooke’s Law,

$$dF = dk \cdot c_1 = P dA,$$  \hfill (2.86)

where $dF$ is the applied force on the infinitesimal portion of the diaphragm, $dk$ is its spring constant, $c_1$ is the displacement, $P$ is the applied pressure, and $dA = dL^2$ is the area, the spring constant is

$$dk = \frac{P dA}{c_1}.$$  \hfill (2.87)

From the relationship between $c_1$ and $P$ shown in Equation 2.51 on Page 68, we obtain

$$\frac{P}{c_1} = \frac{EH^3}{K_E(1 - \nu^2)L^4},$$  \hfill (2.88)

\(^{21}\)At a ratio of 0.188 nm/Pa, even 10,000 Pa of pressure only displaces water by 1.88 $\mu$m.
which yields a spring constant of
\[
\frac{d k}{d L^2} = \frac{E H^3}{K E(1 - \nu^2)L^4} 5.32 \times 10^9 \text{ N/m}^3 \times d L^2.
\] (2.89)

The resonant frequency of a mass-spring system is
\[
f = \frac{1}{2\pi} \sqrt{\frac{d k}{d m}}.\] (2.90)

Substituting the values from Equations 2.85 and 2.89 produces a resonant frequency
\[
f = 54 \text{ kHz}.\] (2.91)

A better approximation of the resonant frequency can be made using [3]
\[
f = 1.654 \sqrt{\frac{E}{\rho(1 - \nu^2)}} \frac{H}{L^2},\] (2.92)

which produces
\[
f = 71 \text{ kHz}.\] (2.93)

Since we are interested in pressure wave frequencies far less than this value, mechanically filtering high frequency signals enable us to ignore the dynamic effects of the resonant behavior of the diaphragms. The constricted channels that connect the cavities beneath the diaphragm to the environment act as the desired mechanical lowpass filters.
2.10 Summary of Expected Performance

The expected performance parameters for the strain-gauge pressure sensors of various diaphragm lengths $L$, as discussed in earlier sections of this chapter, are summarized in Table 2.2. All diaphragms have thickness $H = 20 \mu m$ and all bridge source voltages are $V_s = 10$ V.

Note, however, that the performance parameters are subject to several factors, including the simplifications made to the deflection model (Section 2.6), fabricated size of the diaphragm (Section 3.4), and mask alignment (Section 3.8).

<table>
<thead>
<tr>
<th>Diaphragm Length ($\mu m$)</th>
<th>1000</th>
<th>1414</th>
<th>2000</th>
<th>2828</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ctr. Deflection $c_1/P$ (nm/Pa)</td>
<td>0.0118</td>
<td>0.0470</td>
<td>0.188</td>
<td>0.752</td>
<td>3.01</td>
</tr>
<tr>
<td>Resistance (kΩ)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Sensitivity ($\mu$V/Pa)</td>
<td>0.022</td>
<td>0.043</td>
<td>0.087</td>
<td>0.173</td>
<td>0.347</td>
</tr>
<tr>
<td>Noise ($\mu$V)</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Pressure Resolution (Pa)</td>
<td>5.9</td>
<td>3.0</td>
<td>1.5</td>
<td>0.75</td>
<td>0.37</td>
</tr>
<tr>
<td>Pressure Range (kPa)</td>
<td>169</td>
<td>42.6</td>
<td>10.6</td>
<td>2.66</td>
<td>0.664</td>
</tr>
<tr>
<td>Resonant Frequency (kHz)</td>
<td>282</td>
<td>141</td>
<td>71</td>
<td>35</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 2.2: Expected performance parameters for strain-gauge pressure sensors of various diaphragm lengths $L$.

The pressure sensors with diaphragm lengths $2000 \mu m$ or larger are thus expected to meet the specifications for underwater navigation applications as listed in Chapter 1.
Chapter 3

Fabrication

This chapter describes the fabrication of the sensors. Section 3.1 provides an overview of
the fabrication process flow for Round 4 devices. Section 3.2 describes how the process flows
for devices from Rounds 1, 2, 3a and 3b differ from that for Round 4 devices. Section 3.3
describes the standard photolithographic procedures used in the experiments. Sections 3.4
and 3.5 discuss KOH and Pyrex etching, respectively. Section 3.6 reviews the anodic bond-
ing of silicon and Pyrex wafers. Section 3.7 explains how the process flow was designed.
Section 3.8 describes the designs of the various masks.

Standard integrated circuit (IC) fabrication techniques were used. When processes
differed from common usage, or when special techniques were employed, they are explained
in greater detail. Chemical vapor deposition, oxidation, e-beam evaporation deposition and
spin-on processes were used to deposit uniform layers of material.

For reference, the chemical formulas for the common names and abbreviations used are
given in Appendix A. Key standard operating procedures (SOPs) used for the process flows
are given in Appendix B. Appendix C contains the complete process flows, specific recipes
and descriptions of machines used. Appendices D and E shows the masks and technical
diagrams of the various apparatus, respectively, used during fabrication.

All processing, except where noted otherwise, was done in the Technology Research Lab-
oratory (TRL) and Integrated Circuits Laboratory (ICL) facilities of the MIT Microsystems
Technology Laboratories (MTL).
3.1 Overview of Fabrication of Round 4 Devices

The process flow for Round 4 devices is described below. The variations on this fabrication process for earlier rounds of devices are listed in Section 3.2. The process flow for Round 5 devices is described in Section 5.3.

The silicon-based sensors start with a Silicon-On-Insulator (SOI) wafer, which is comprised of a thin (20 µm) (100) silicon wafer (called the front-side, or device wafer) bonded to a standard-thickness (650 µm) (100) silicon wafer (called the back-side, or handle wafer) through a thin (less than 1 µm) layer of silicon oxide, an electrically insulating material. SOI wafers were chosen as the initial substrates because they are readily available with front-sides ranging from less than one micron to tens of microns, the desired thicknesses for the thin wafer to act as the pressure-sensing diaphragm.

First, silicon nitride is deposited on both sides of the SOI wafer. The front-side nitride is then etched, using a photolithographically-defined etch mask and a reactive-ion etcher, to expose most of the front-side thin silicon and leave a nitride ring at the outer portion of the front-side. Next, silicon oxide is grown on the front-side to insulate the semiconducting silicon from the resistors, which sit on the oxide. The back-side nitride is then etched to open square windows in the shape of the diaphragms. Finally, the silicon is anisotropically etched in potassium hydroxide (KOH), with the nitride and the original oxide acting as an etch mask and an etch stop, respectively. The KOH etch results in the release of the square silicon diaphragms suspended over open cavities.

A Pyrex wafer is used to close the open cavities. To do so, channels are etched into the Pyrex wafer using hydrofluoric acid and a chromium-gold etch mask. The etched face of the Pyrex wafer is its front-side and the clean reverse face is its back-side. After the SOI wafer and the Pyrex wafer are anodically bonded together, resistors are etched into a metal film deposited by thermal evaporation of the front-side. Finally, a thin layer of Parylene polymer is deposited on the front-side to waterproof and electrically insulate the resistors from the aqueous environment. Optionally, single pressure-sensing cells, or entire pressure-sensing arrays, are separated from the bonded wafer pair by die sawing, and subsequently packaged.
3.1. OVERVIEW OF FABRICATION OF ROUND 4 DEVICES

for testing.

A graphical representation of the process flow for Pyrex alone can be found in Subsection 3.5.2. A graphical representation of the remaining device process flow for Round 4 devices is presented below. Only graphics where the wafer shape or layers change are shown; changes between cleaning steps are not depicted. The step numbers correspond to the complete process flow shown in Appendix Section C.3.

15 Start with SOI wafer

![Diagram of SOI wafer]

16 Deposit nitride

![Diagram of deposited nitride]

17–20 Remove some nitride from front-side, leaving a nitride ring on the outer portion

![Diagram of removal of nitride]
21–22 Grow oxide on front-side

23–30 Pattern back-side

31–35 KOH etch back-side to create diaphragms

36–37 Anodically bond SOI and Pyrex wafers
3.1. OVERVIEW OF FABRICATION OF ROUND 4 DEVICES

38–39 Evaporate Cr/Au on front-side

40–44 Etch Cr/Au to create resistors

45 Deposit Parylene on front-side
3.2 Variations on Fabrication for Rounds 1, 2, 3a and 3b

The differences between the process flows for devices from Rounds 1, 2, 3a and 3b and the process flow for Round 4 devices are listed below. These are summarized in Table 3.1 at the end of this section.

Truncated process flow

- Round 1 devices do not have resistors; the process flow ends at Step 37. Furthermore, the front-side nitride is not etched and insulating oxide is not grown.

- Round 2 devices consist of resistors on dummy wafers. Fabrication consists solely of Steps 38–44 performed on dummy silicon nitride wafers.

- Round 3a and 3b devices do not have a waterproofing Parylene layer; the process flow ends at Step 43.

- Only Round 4 devices have a gold-on-chromium (Au-on-Cr) double-layer metal film as the resistors. Devices from Rounds 1, 2, 3a and 3b have only chromium as the resistor material. The reason for adding the gold is discussed in Section 4.4.

Extra steps that were later removed

- Round 1 and 3a devices have an additional KOH etch step at the beginning of the process flow after nitride is deposited in order to find the crystalline plane. This procedure can be found in Appendix Section C.2. The reason this step was later discarded is discussed in Subsection 3.4.2.

- Round 1 devices have an additional step before silicon-Pyrex bonding: The nitride envelope, including the back-side nitride, is completely stripped from the SOI wafer in hot phosphoric acid. As discussed later in Section 3.6, this step was found to be unnecessary and was thus discarded for subsequent rounds.
3.2. VARIATIONS ON FABRICATION FOR ROUNDS 1, 2, 3A AND 3B

Purpose of step altered

- Round 1, 3a, 3b and 4 devices all have the front-side nitride etched prior to oxide growth. However, the features left on the nitride and their purposes differed. In Rounds 1 and 3a, there is no ring of nitride around the front-side. Instead, only small alignment marks are left in the nitride and the rest of the nitride is removed. In Rounds 3b and 4, the nitride ring is maintained, and, as discussed in Section 3.8, the aforementioned alignments marks are incorporated into the mask for this step. The purpose of the nitride ring is discussed in Subsection 3.4.3.

Steps in different order

- Round 3a devices have metal deposition and etching done before KOH etching. The reason for later switching the order for Round 3b and 4 devices is discussed in Subsection 3.7.1.

Summary

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3a</th>
<th>3b</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extra KOH etch</strong></td>
<td>Yes</td>
<td></td>
<td>(No KOH at all)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Layer above diaphragm</td>
<td>Nitride</td>
<td>Oxide</td>
<td>Oxide</td>
<td>Oxide</td>
<td>Oxide</td>
</tr>
<tr>
<td><strong>Front-side nitride etch</strong></td>
<td>Alignment only</td>
<td>(No nitride)</td>
<td>Alignment only</td>
<td>Alignment + ring</td>
<td>Alignment + ring</td>
</tr>
<tr>
<td><strong>Back-side nitride</strong></td>
<td>Remove</td>
<td>(No nitride)</td>
<td>Retain</td>
<td>Retain</td>
<td>Retain</td>
</tr>
<tr>
<td><strong>Metal(s) for resistors</strong></td>
<td>(No resistors)</td>
<td>Cr</td>
<td>Cr</td>
<td>Cr</td>
<td>Au-on-Cr</td>
</tr>
<tr>
<td>Metal &amp; KOH</td>
<td>KOH only (no resistors)</td>
<td>Metal only (no diaphragms)</td>
<td>Metal, then KOH</td>
<td>KOH, then metal</td>
<td>KOH, then metal</td>
</tr>
<tr>
<td>Parylene</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 3.1: Variations on fabrication for Rounds 1, 2, 3a, 3b and 4.
3.3 Photolithography

All photolithography was performed with the following tools, which can achieve feature sizes and alignment accuracies under 1 $\mu$m.


- **EV1**: Electronics Visions Model EV620 Mask Aligner.

- **Developing Station**: Semifab Model WPS 800 Wet Processing Station.

Two positive photoresists (PR) were used:

- **AZ 917**: Default PR on blank glass-chromium masks.

- **OCG 934**: PR for all other photolithographic steps.

Appendix Section C.1 contains the process flow for all photolithography steps. Appendix Sections B.1 and B.2 describe the mask-making and photolithography standard operating procedures, respectively, in detail.

Figure 3-1 depicts the procedure for transferring the features from a glass-chromium mask to the photoresist on a substrate wafer. Each mask is a square 7" by 7" glass plate with the intended pattern etched onto a thin chromium film on one face of the plate. The mask is loaded chromium-side down into EV1. The wafer, spin-coated with photoresist on one or both sides, is loaded into EV1 such that the chromium side of the mask is 30 $\mu$m above the photoresist layer. The wafer is exposed to 365-405 nm wavelength ultraviolet (UV) light through the mask for 2.3 seconds.

Since UV light cannot pass through chromium, the areas of the resist directly below any chromium are left unchanged. Sensitizer materials in the exposed resist below open regions of the mask, however, are broken down by the UV light. Once the wafer is placed in a developer bath, the exposed photoresist washes away, revealing the original substrate. Thus, the pattern in the mask is now transferred to the photoresist.
3.3. PHOTOLITHOGRAPHY

Figure 3-1: Standard photolithography. (a) UV light affects the areas of resist not covered by chromium. (b) After developing, exposed areas of resist are washed away.

The following process, depicted in Figure 3-2, was used to produce most\(^1\) of the glass-chromium masks used for photolithography. First, the mask design is printed on a transparent 100 µm polymer-based film by PageWorks, Inc. in Cambridge, Massachusetts. The high-quality emulsion-based imagesetting films are printed emulsion side up using Heidelberg technology at 5080 dpi, which translates to a spacing of 5 µm per dot. The transparency mask is transferred to a blank chromium mask in the following manner. A triple stack of plates is prepared: (a) a blank glass-chromium mask is placed on the bottom with the chromium and resist side up; (b) the transparency is in the middle with the ink side down; (c) a clean glass plate is placed on top. It is important for the ink side of the transparency to be in hard contact with the chromium/resist side of the mask so that the transparency features are transferred accurately. The stack undergoes flood exposure for 5.0 seconds and the resist is developed. The chromium layer is patterned by etching the exposed chromium

\(^1\)The masks for forming the strain-gauge resistors, Mask R, was instead directly laser-printed to a 7” glass-chromium mask by Advanced Reproductions because these masks require a much higher resolution in order to ensure that the resistors have precise dimensions and do not have breaks.
Figure 3-2: Mask-making process. (a) UV light affects the areas of resist not covered by chromium. (b) After developing, exposed areas of resist are washed away. (c) Exposed chromium is etched away. (d) Remaining resist is removed.

Finally, the resist is stripped. The glass-chromium mask is now ready for use.
3.4 Potassium Hydroxide Etching of (100) Silicon

Etch processes are categorized based on the nature of the etching agent. If the etchant is a liquid in which the wafer is immersed, the etch is *wet*, otherwise the etch is *dry*. Additionally, if the wafer is etched equally in all directions, the etch is *isotropic*, and if the wafer is etched preferentially in one or more directions, the etch is *anisotropic*. This second categorization is not binary, and there is a continuous measure of how isotropic a particular etch is. Both types of categorizations are independent, and Table 3.2 shows diagrams of examples of the profiles from the four possible combinations of etch types.

Two wet etch technologies were used, one for each type of wafer.

1. Hydrofluoric (HF)-based etching of Pyrex glass (isotropic process);

2. Potassium hydroxide (KOH)-etching of (100) silicon (anisotropic process).

HF on Pyrex is an isotropic etch, and any surface-level shape for the etch cavity can be created. KOH on (100) silicon, on the other hand, is an anisotropic etch, and all etch cavities are shaped as rectangles with edges parallel and perpendicular to the wafer flat as viewed from the wafer surface [73, 56].

![Diagram of cross-sectional trench profiles resulting from four different types of etch methods. Reproduced from [56].](image)

Potassium hydroxide in solution (KOH) etches silicon anisotropically by the redox re-


\[ \text{Si} + 2\text{OH}^- \rightarrow \text{Si(OH)}_2^{+2} + 4e^-, \quad \text{(oxidation)} \quad (3.1) \]

\[ \text{Si(OH)}_2^{+2} + 4e^- + 4\text{H}_2\text{O} \rightarrow \text{Si(OH)}_6^{-2} + 2\text{H}_2. \quad \text{(reduction)} \quad (3.2) \]

KOH etches \{100\} planes about 400 times faster\(^2\) than it etches \{111\} planes. The vast difference in etch rates results in KOH-etch features in the silicon crystal with faces made up only of \{111\} planes [56]. Figure 3-3 shows examples of cavities formed by KOH-etching (100) silicon. When (100) silicon is KOH-etched, the walls of the cavity produced form 54.7\(^\circ\) angles with the surface plane, and such walls get closer to one another as the depth increases, forming trenches or self-terminating valleys. Furthermore, the shape of the cavity at the surface is always rectangular and bounded by lines in the \langle 110 \rangle direction. Thus, if the mask used is not bounded as such, the boundaries will grow to the smallest \langle 110 \rangle-bounded rectangle that contains the mask. If the width of the exposed surface of the wafer is sufficiently small compared to the thickness of the wafer, the etch will self-terminate when a V-shaped groove is achieved.

The remainder of this section discusses KOH etching in greater detail. The standard operating procedure for KOH etching is in Appendix Section B.3. This is always followed by the post-KOH cleaning procedure described in Appendix Section B.4.

### 3.4.1 Silicon nitride mask and silicon oxide etch stop

Silicon nitride (Si\(_3\)N\(_4\)) is deposited on silicon by low-pressure chemical vapor deposition (LPCVD) to be used as a mask for KOH etching. Either of the following reactions is used [66]:

\[ 3\text{SiH}_2\text{Cl}_2 + 4\text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + 6\text{HCl} + 6\text{H}_2, \quad (3.3) \]

\[ 3\text{SiH}_4 + 4\text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + 12\text{H}_2. \quad (3.4) \]

\(^2\)[92, 93] list the etch rates for a wide variety of etchants and substrates. The exact etch rate is highly dependent on the concentration and temperature of the KOH solution. This thesis used a 20% (by mass) KOH solution at 80\(^\circ\)C, which etches (100) silicon at a rate of approximately 80 \(\mu\text{m/hr}\). Thus, the etch takes about 8 hours.
Figure 3-3: Examples of KOH-etching (100) silicon: (a) trenches, self-terminating V-shaped grooves and inverted pyramids; (b) etching from both sides of the wafer. Reproduced from [56].
KOH slowly degrades nitride, but we found that 0.1 μm of nitride was able to withstand KOH long enough for 650 μm of silicon to be etched. Thin layers of nitride are desirable as an unnecessarily thick nitride layer can contribute to thermal stress on the wafer.

A 1 μm (10,000 Å) silicon oxide layer is sandwiched between the 20 μm device wafer and 650 μm handle silicon wafer in the manufactured SOI wafers. This oxide layer serves as an etch stop, which prevents the KOH solution from etching the thin device wafer that forms the silicon diaphragms.

3.4.2 Finding the crystalline plane

Since KOH-etching (100) silicon produces rectangular features along the ⟨110⟩ directions, aligning masks to the axes of the crystalline plane is important. When the diaphragms are etched, a slight rotation in the rectangular windows framed by nitride with respect to the crystalline axes would result in features that are larger than the intended sizes, causing other features to misalign. Although the wafer flat is supposed to be along a ⟨110⟩ direction, real wafers are tilted from this ideal position by up to one degree of angle measure. To find the ⟨110⟩ directions, a special KOH etch mask and process is used. This etch transferred Mask N, which contains a series of hundreds of long, narrow rectangles oriented at angles in increments of a hundredth of a degree off the wafer flat. Thus, by observing the etch patterns of the rectangles under a microscope, the user can determine to very high accuracy the angles of the ⟨110⟩ directions relative to the wafer flat.

As discussed in Section 3.2, Round 1 and 3a devices have this additional KOH etch step at the beginning of the process flow after nitride is deposited in order to find the crystalline plane. The procedure can be found in Appendix Section C.2. However, the extra KOH etch step weakens the wafer and renders it extremely brittle after the second KOH etch that creates diaphragms. Several Round 1 wafers broke in this manner. At first, it was believed that the large rectangular holes on the sides of the second KOH mask (Figure D-4) affected the structural integrity of the wafer. Thus, for Round 3a, those holes were removed (Figure D-6). However, even after this improvement, two Round 3a wafers were lost after the second KOH etch. Furthermore, pinholes in the nitride mask allow the KOH to etch
3.4. **POTASSIUM HYDROXIDE ETCHING OF (100) SILICON**

small pyramidal dimples on the surface, making it difficult for other fabrication tools to clamp onto the back-side silicon by vacuum suction. Since the plane-finding KOH etch would occur early in the fabrication process to align subsequent masks to the crystalline plane, future processing steps are affected.\(^3\)

In the end, however, the \(<110>\) directions were found to be sufficiently close to the wafer flat that the crystalline-finding KOH etch was not necessary. Due to the risks with wafer weakening and back-side suction discussed above (not to mention the additional time spent with photolithography, etching, cleaning and observing), this step is not worth taking. Thus, the process flows for Rounds 3b and 4 discard the crystalline-finding KOH etch step. These rounds assume the SOI wafer flat is parallel to a \(<110>\) direction.

### 3.4.3 Mechanical wafer protection

Because protective nitride is removed from, and insulating oxide is grown on, the front-side of the SOI wafer before KOH etching the back-side silicon (the rationale for this is discussed in Subsection 3.7.2), KOH etching is done with special care. The KOH solution envelopes the entire wafer, etching any region, both silicon and oxide (albeit at different rates), that is unprotected by nitride.

To protect the front-side device wafer, the wafer is placed inside a custom-made KOH wafer holder that only allows one side of the wafer to be exposed to the KOH solution (Figure 3-4). The wafer holder, which holds one wafer at a time, is a circular apparatus made of polytetrafluoroethylene (PTFE). It consists of a bottom plate and a top ring both with grooves to hold O-rings of diameters slightly smaller than that of the wafer. The wafer is sandwiched between the O-rings of the bottom plate and top ring back-side up, and the whole assembly is held together by 12 screws. When the loaded apparatus is placed in the KOH solution, the top O-ring prevents KOH solution from seeping to the edge of the wafer. As a secondary precaution, even if some KOH solution leaks through the top O-ring, the bottom O-ring prevents KOH solution from reaching the protected wafer side.

---

\(^3\)Note that this is not an issue for the KOH etch that creates the diaphragms. The silicon wafer is bonded to Pyrex immediately after that etch, and subsequent processing handles the clean back-side of the Pyrex wafer.
CHAPTER 3. FABRICATION

Figure 3-4: Side view of KOH wafer holder. The wafer is placed front-side down to expose the back-side to KOH. The black circles represent the cross-section of the O-rings. Only the exposed silicon comes into contact with KOH solution, which surrounds the apparatus, and the oxide layer (violet) is protected.

Figures E-1, E-2 and E-3 in Appendix E depict the technical diagrams of the KOH wafer holder from the top and bottom views.

Use of the wafer holder requires special care. Uneven stress from the mounting screws can cause the wafer to crack. Thus, in order to ensure that the wafer is loaded under uniform stress, the user tightens the 12 screws gradually by only turning each screw a few rotations before moving on to a screw at the opposite end of the wafer holder, much like installing an automobile tire. Additionally, the wafer is first rinsed after the KOH etch while still loaded in the wafer holder. Even after this rinse, some KOH solution may still be lodged between the O-rings and the wafer. Thus, a second 15-minute cascade rinse on the bare wafer out of the holder removes any residual KOH.

As discussed in Section 3.2, in Rounds 1 and 3a, there is no ring of nitride on the front-side of the device wafer. Instead, the front-side is all oxide. Thus, if some KOH solution manages to leak through the top O-ring, it would begin to attack the oxide outside the bottom O-ring. Although silicon oxide can serve as an etch stop for KOH, it does not hold up against KOH as well as nitride does: Since the grown front-side oxide is only 0.1 µm (1000 Å) thick,\(^4\) it would take less than an hour for the KOH to etch through completely at

\(^4\)In contrast, the oxide etch stop sandwiched between the device and handle wafers is 1 µm (10,000 Å) thick.
a rate of approximately 20 Å/min. Furthermore, once some oxide is etched, the KOH can tunnel under the bottom O-ring to reach the device portion of the oxide layer. In one Round 3a wafer, this leakage did indeed occur, rendering the wafer unusable. Thus, in Rounds 3b and 4, a ring of front-side nitride is maintained to serve as a second line of defense in case the top O-ring doesn’t perfectly block KOH.

As mentioned earlier in Subsection 2.2.4, Round 3b wafers further differed from Round 3a wafers in that the four sensors at the corners of the wafer were removed. Those the back-side nitride windows that create those diaphragms happen to overlap with the top O-ring. Thus, as the cavity directly in contact with the O-ring is etched in the KOH solution, the solution is able to tunnel under the top O-ring and possibly attack some of the oxide on the other side of the wafer. When this effect was discovered, the masks were corrected by removing those four sensors.
3.5 Pyrex Etching

The air channels of the strain-gauge pressure sensors are etched in a Pyrex glass wafer. The bond between the silicon and Pyrex wafers seals the cavities beneath the silicon diaphragms. Due to the importance of these device features, this section describes Pyrex etching in detail, including the substrate material, the process flow, process design, the masking materials, choices for Pyrex etchants, and the importance of retaining photoresist on the gold mask. Pyrex wafers with appropriate air channel characteristics and very good anodic bonding surfaces\(^5\) were successfully fabricated.

3.5.1 Substrate material

The Pyrex glass used in this thesis is Corning Pyrex 7740, a substrate that consists of 81% SiO\(_2\), 13% B\(_2\)O\(_3\), 4% Na\(_2\)O and 2% Al\(_2\)O\(_3\). Pyrex 7740 is commonly used for anodic bonding to silicon due to its high content of mobile sodium ions and matching thermal expansion rates [92]. Furthermore, compared to other glasses, 7740 does not have as much deposition of residual products on the generated etch surfaces [48], which would roughen the surfaces and reduce etch rate uniformity. Significant amounts of substances other than SiO\(_2\) considerably alter the etching characteristics as compared to the well-studied SiO\(_2\) [92].

3.5.2 Process flow for etching Pyrex

A graphical diagram of the process flow for etching Pyrex is summarized below. The step numbers match those in Table 3.3, as well as in the Pyrex-etching portions of the device process flows in Appendix C.

1–6 Clean wafer (blue) and evaporate chromium (gray) and gold (yellow) on both sides

\(^5\)See Section 3.6 for a discussion about experiments that verified this.
3.5. *PYREX ETCHING*  

7a Coat photoresist (PR) on both sides

7b Photolithography on front-side

8–9 Etch front-side gold and chromium

10 Etch Pyrex

11 Strip photoresist from both sides

12–13 Remove remaining gold and chromium from both sides

To reduce the number of pinholes, the Pyrex must be very clean prior to metal deposition, as any particles or organics on the surface would prevent bonding between the
Table 3.3: Process flow for etching Pyrex wafers. It can also be found in Appendix C as part of the complete process flows for device fabrication.

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>2</td>
<td>Clean</td>
<td>TRL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>3</td>
<td>Metal</td>
<td>TRL</td>
<td>E-beam</td>
<td>Standard</td>
</tr>
<tr>
<td>4</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>5</td>
<td>Clean</td>
<td>TRL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>6</td>
<td>Metal</td>
<td>TRL</td>
<td>E-beam</td>
<td>Standard</td>
</tr>
<tr>
<td>7</td>
<td>Photo (front)</td>
<td>TRL</td>
<td>Coater/EV1</td>
<td>Standard (double-sided)</td>
</tr>
<tr>
<td>8</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>9</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>10</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>11</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>12</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>13</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>14</td>
<td>Storage</td>
<td>TRL</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
3.5. **PYREX ETCHING**

Pyrex and metal. There is much work reported in the literature regarding cleaning glass surfaces for adhesion [1, 13]. For this thesis, the following cleaning procedure was used. First, the Pyrex is placed in freshly prepared piranha (3:1 H$_2$SO$_4$:H$_2$O$_2$) for 10 minutes at 120°C, which removes organic matter. After the wafers are rinsed in distilled water, they are dipped in 50:1 H$_2$O:49% HF for 15 seconds, etching the Pyrex by a microscopic amount to undercut any remaining particles. The wafer is then rinsed thoroughly to remove all HF and then spun dry. If desired, the wafer may then be ashed to further remove organics, but in this thesis, this step was found to be unnecessary. It should also be noted that this cleaning process assumes the Pyrex is already in the clean condition as prepared by the manufacturer. If it is not, then other steps should be taken prior to the piranha clean.

Immediately after the wafer is cleaned, the wafer is placed in the metal mask deposition machine. An electron beam evaporator was used to deposit chromium and gold; the metals were deposited in succession in the same vacuum. 200 Å of Cr and 1000 Å of Au are sufficient. Thicker metal layers act as better masks, but the improvement may not be worth the higher fabrication costs. A slower deposition rate generally produces a more uniform thickness across the wafer. A deposition rate of 3 Å/s was used for both metals. It is important for the two metals to be deposited in immediate succession. Exposing the chromium surface to air would enable chromium oxide (CrO) to form, which etches in the Pyrex etchants. Although the standard operating procedure for the machine calls for a pressure of 2.0 × 10$^{-6}$ Torr (or mmHg), much lower vacuum pressures in the range 1.9 × 10$^{-7}$ to 2.7 × 10$^{-7}$ Torr was used. The higher-quality vacuum creates a cleaner metal surface since there are fewer extraneous particles in the space. This generally requires pumping down the machine overnight. Since the e-beam evaporator only deposits on one side of a wafer at a time, the wafer cleaning and metal deposition processes are then repeated for the other side of the wafer. Gold scratches easily, so it is very important to ensure that solid tools do not unnecessarily touch the metal surface in all subsequent steps.

Once the metal mask has been prepared, standard double-sided photolithography with a photoresist thickness of 1 µm is done. As usual, photoresist is first spun on the side that will not be etched (back-side). Although the integrity of the photoresist on the back-
side is generally not as crucial as the front-side, it should be noted that for some of the process flows in this thesis, the Pyrex is later bonded to an SOI wafer and undergoes further photolithography. Thus, the back-side Pyrex must be smooth enough after Pyrex etching to provide even contact with the vacuum chuck of the spin steps. Since, for this thesis, protecting the back-side is just as important as protecting the front-side, extra care is taken to ensure that the spin coater is clean so that during front-side coating, the back-side photoresist is not disturbed. As a further precaution, extra photoresist can be brushed on the back-side by hand, but this was not done in this thesis.

Next, the pattern from the photoresist is etched into gold. There are two choices of gold etchants:

- Gold etchant thin film type A (TFA): 30% potassium iodide (KI), 1.3% iodine (I$_2$), 68.7% water (H$_2$O);

- Aqua regia: 3 hydrochloric acid (HCl) : 1 nitric acid (HNO$_3$).

Either choice was found to be suitable. The wafer is thoroughly rinsed and then the chromium is etched in Cr-7 (9% (NH$_4$)$_2$Ce(NO$_3$)$_6$ + 6% HClO$_4$ + H$_2$O). The wafer is thoroughly rinsed again. The gold etchant does not etch the photoresist and Cr-7 etches neither the photoresist nor the gold. The wafer should be removed from the etchants as soon as possible, as over-etching will cause undercutting of the metal masks.

The wafer is now ready for Pyrex etching. A solution of 660:140:200 H$_2$O:HNO$_3$:HF is prepared. The wafer is placed in the solution for a timed etch front-side up so that bubbles do not collect on the etching surface. It should be noted that during the metal and Pyrex etching, the sides of the wafers are completely bare. Furthermore, since the wafer sits on a narrow rim in the e-beam evaporator, a 1-mm wide rim on the outside of the wafer is left without metal on either side as well. Thus, the edges of the Pyrex are etched away. This effect should be taken into account for mask design if the features run to the edge.

The wafer is then thoroughly rinsed. The masks (photoresist, gold, chromium) are then successively removed. This completes the Pyrex etching process.
3.5.3 Process design for etching Pyrex

The process described in the previous subsection was developed after a literature review and experiments that explored the various masks materials and wet etchants were conducted. The results of this research is discussed in the remainder of this section on Pyrex etching.

There are several choices for etching types and recipes, all with various advantages and disadvantages. To pick the most appropriate process, the following specifications were considered. The etch should be fast enough so that channels of depth 50 µm to 100 µm can be etched in a reasonable amount of time, but not so fast as to result in unreliable or inconsistent features. The etch mask must be strong enough to prevent the formation of extraneous canals that would connect channels together at undesired locations. The surface must remain smooth enough to anodically bond with silicon. Other requirements, such as sidewall smoothness, high uniformity and isotropicity, are not important for this thesis.

3.5.4 Masking materials

All the wet Pyrex etchants lift off a photoresist layer spun directly on Pyrex because photoresist does not adhere strongly enough to Pyrex. Fortunately, photoresist adheres well to metal, so metal masks, in place of phororesist, are necessary to etch Pyrex successfully. A successful mask must satisfy four conditions: (1) it does not cause damage to the Pyrex substrate during its deposition; (2) it can be etched with photoresist as an etch mask; (3) it can stand up to the Pyrex etchant; and (4) it leaves the Pyrex surface smooth after its removal. Although several silicon-based materials, such as amorphous silicon, polysilicon, bulk silicon and silicon carbide, are possible and have been reported in the literature [88, 80, 49, 48, 5], this thesis used a multilayer metal film as the mask for etching Pyrex. Since gold is an inert material in all the wet etchants considered, it was used as the etch mask, with an adhesion layer of chromium deposited between the Pyrex wafer and the gold layer [5]. Table 1 in [48] provides an overview of various masking materials.

The success of an etch is extremely sensitive to the quality of the metal masks. Since wet Pyrex etches are nearly isotropic, a microscopic pinhole in the metal masks will lead to a hemispheric dimple in the Pyrex. If there are sufficiently many pinholes, then not only
is the quality of the bonding surface compromised, but such dimples can merge with one another and create unwanted canals between the etched channels. Another type of defect is notching defects on the edges of the metal mask. Both pinholes and notching defects can be caused by the tensile stress induced in the metal masks during the cooling process after deposition. The cooling process creates creeps in the metal [80] as well as causes freestanding metal to break as the metal is undercut during the isotropic Pyrex etch [49]. The Pyrex etchant seeps into these creeps and produces pinholes.

One way to reduce the stress is to anneal the metal; however, annealing can also diffuse gold into the chromium layer, which reduces the efficacy of the mask. Annealing also has the side effects of increasing the Pyrex etch rate due to a redistribution of oxides [49] and roughing the etch surface [48].

In addition to protecting both sides of the Pyrex wafer during the wet Pyrex etch, the double-sided metal layers also stabilize the stress characteristics of the wafer [80]. The stress induced by the deposition on one side nearly cancels out that induced on the other side. Thus, identical deposition procedures should be followed for both sides, as the stress is dependent on the process parameters and equipment.

Because of the tensile stress from metal masks, some applications prefer a masking layer, such as amorphous silicon or polysilicon, with compressive stress instead of tensile stress [49]. Another advantage that silicon-based masks provide is a hydrophobic surface, which causes pinholes and notches to repel wet Pyrex etchants. However, silicon-based masks are comparatively more difficult to deposit and to remove with the tools available for this thesis and were therefore not attempted. Furthermore, the surface of a metal mask can be made sufficiently hydrophobic by leaving photoresist on it.

It has been reported that performing multiple (three or four) depositions of gold with a cooling time of 30 minutes in between depositions reduces the number of pinholes [49], since successive depositions cover the defects in the previous layer. Such masks are of very high quality. However, this procedure was not used in this thesis since the number of pinholes from a single metal deposition was sufficiently low for the desired application.
3.5.5 Pyrex etchants

There is a good selection of HF-based etchants for Pyrex available; an overview of their mechanisms is given in [77]. When the author of this thesis was working on tunable MEMS resonators, several preliminary experiments on wet-etching Pyrex were conducted [46]. First, buffered oxide etch (BOE), a 5:1 mixture of 40% ammonium fluoride (NH₄F) and pure 49% hydrofluoric acid (HF)⁶, was used; it was found to etch too slowly. Thus, pure 49% HF was tested instead, but standard OCG photoresist could not withstand HF long enough to serve as a mask. Furthermore, replacing OCG with an SU-8 polymer photoresist did not solve this problem. Others have successfully studied deep etching of Pyrex in 49% HF [80, 49], but due to safety concerns with highly concentrated HF, their processes were not attempted. Finally, the etch solution 660:140:200 H₂O:HNO₃:HF, which has an etch rate of approximately 0.8 µm/min, was found to work well. The nitric acid removes the impurities from the Pyrex, and the HF etches the remaining SiO₂.

3.5.6 Importance of retaining photoresist on gold

It is important to retain the photoresist layer over the gold layer during wet etching of Pyrex. Although gold stands up to HF, BOE and the 660:140:200 H₂O:HNO₃:HF solution, microscopic pinholes in the chromium and gold layers expose Pyrex to the etch solution, which create unwanted hemispheric dimples on the wafer surface. By keeping the photoresist over the metal layers during the Pyrex etch, the pinholes are covered. Highly concentrated HF etchants will eventually lift off a photoresist layer, but the photoresist that fills in the pinholes remain for a much longer period of time because of high adhesion to the cracks and limited contact area with the etchant. Although some work reported hard-baking the photoresist at 120°C for 30 minutes [80], this was not found to be necessary.

Several experiments confirm that photoresist is necessary. First, the photoresist was removed using piranha after gold was etched but before chromium and Pyrex are etched. When the wafer was placed in Cr-7 to etch the chromium, the entire metal lifted off in large pieces. Second, on another wafer, photoresist was removed using piranha after both gold

⁶“Pure 49% HF” is a solution that consists of 49% HF and 51% H₂O by volume.
and chromium were etched but before Pyrex was etched. During Pyrex etching, the metal lifted off on a microscale and numerous hemispheric dimples were etched into the Pyrex. To summarize both experiments, removing photoresist before the Pyrex is etched causes the metal mask to lift off in the etch step immediately following photoresist removal.

Problems with metalization and the effect of piranha on the metal can both be ruled out as explanations for the results of the above two experiments. Wafers that were successfully etched using the standard procedure were metalized at the same time under the same conditions as the wafers used in the experiments. Also, all wafers have metal on one side exposed to piranha. After metal has been deposited on one side, the wafers are cleaned again in piranha and diluted HF in preparation for metal deposition on the other side.

A final experiment demonstrated that photoresist inside the pinholes is crucial. Removing photoresist using acetone and isopropanol (IPA) instead of using piranha was done as well. This procedure is not as thorough as a piranha strip, so the photoresist over the microsized pinholes, which adheres much more strongly to the metal as compared to surface photoresist, may not be completely removed. The removal was done prior to metal etching. The metal mask was left intact after the entire etch process and the resulting wafer surface was comparable to that of leaving the entire photoresist layer on during the Pyrex etch. The hypothesis that photoresist remained on the metal is confirmed by the observation that after gold etchant and Cr-7 were applied multiple times, numerous specks of metal, protected by photoresist, remained. Others reported similar results [49].
3.6 Anodic Bonding

The silicon and Pyrex wafers are anodically bonded together to seal the air cavities beneath the diaphragms and the air channels that connect the cavities. In this process, the wafers are placed in contact with each other in a vacuum, heated to 350°C and an electric potential of 1000 V is applied across the sandwich, with the silicon at the higher potential. The potential induces migration of sodium ions from the Pyrex wafer into the silicon wafer, resulting in a net negative charge for the Pyrex wafer, and a net positive charge in the silicon. The two charged surfaces then are brought into intimate contact and the heat fuses the two wafers together. The recipe for anodic bonding used in all device fabrication is given in Appendix Section B.6.

As discussed in Section 3.2, Round 1 devices have an additional step before silicon-Pyrex bonding: The nitride layer is completely stripped from the SOI wafer in hot phosphoric acid. However, this is a violent procedure that frequently shatters wafers. Furthermore, the dry etches used to remove nitride (such as for creating the nitride ring) are inappropriate for back-side removal because they can roughen the silicon surface to the extent that an air-tight bond with Pyrex cannot take place. In subsequent rounds of device fabrication, nitride stripping was discarded, and Pyrex was successfully bonded to silicon wafers that had the back-side nitride layer still intact. Thus, sodium ions can migrate through thin nitride films on the surface of a silicon wafer.

An experiment demonstrated that the anodic bond is indeed air-tight. Recall that Round 3a wafers have nine columns of ten devices each, where the cavities in the devices of the same column are connected via air channels etched in Pyrex. There are no outlets to the atmosphere. Before bonding one particular Round 3a wafer set, three of the nine columns each had one diaphragm broken (thus allowing those cavities access to the environment), and the other six columns had all their diaphragms intact. Since anodic bonding occurs in a vacuum, an air-tight bond would deform the diaphragms of the six intact columns inwards. Contrastingly, the diaphragms of the other three columns should remain flat. This is, in fact, what was observed. Furthermore, when five of the six intact columns later had one

---

7The procedure is given in Appendix Section B.5.
diaphragm carefully broken, thus exposing the entire column to atmospheric pressure, the other diaphragms in that column immediately popped back to their flat equilibrium state. The last of the six columns was kept intact for several months without any of the diaphragms popping back. This experiment also showed that the Pyrex etching process described in Section 3.5 produces sufficiently few pinholes that the air channels do not have additional etched canals to connect them.
3.7 Process Design

Several issues were considered in designing the Round 4 process flow, including the order in which fabrication steps are done, ensuring that diaphragms do not deform when placed in a vacuum, and ensuring that wet processes do not damage internal channels. None of these decisions were affected by the desire to add transistors in Round 5.

3.7.1 Order of key steps

The order of four key fabrication steps, listed below, is considered.

- Pattern metal to create resistors;
- Deposit metal;
- KOH-etch cavities into silicon wafers;
- Bond silicon and Pyrex wafers.

The order is subject to four constraints:

1. Patterning metal must occur after the metal has been deposited onto the wafer in the first place.
2. Depositing metal must occur after KOH-etching.
3. Bonding must occur after KOH-etching.
4. Patterning metal cannot occur between KOH-etching and bonding.

The second constraint is needed because the piranha in post-KOH clean, which implicitly follows any KOH etch, attacks chromium metal. The third constraint exists because the back-side of the SOI wafer is sealed from further processing after it has been bonded to the Pyrex wafer. The fourth constraint exists because the KOH etch step creates open cavities on the back-side of the silicon wafer. However, any photolithography step, which metal patterning includes, requires the wafer chuck of the photoresist coater to come into contact
with the back-side. The cavities make it difficult for the wafer chuck to make a reliable vacuum seal with the back-side. After the Pyrex wafer is bonded, though, the non-bonded side of the Pyrex wafer can serve as the handle for the chuck.

Thus, two different permutations of key fabrication steps are possible:

**Order A**

1. KOH-etch cavities into silicon wafers;
2. Bond silicon and Pyrex wafers;
3. Deposit metal;
4. Pattern metal to create resistors.

**Order B**

1. KOH-etch cavities into silicon wafers;
2. Deposit metal;
3. Bond silicon and Pyrex wafers;
4. Pattern metal to create resistors.

Note that both permutations have the relatively high risk step of KOH etching as early as possible, which is desirable. Of all the steps in the Round 4 process flow, KOH etching has the highest chance of wafers breaking or being damaged beyond use as a result of the step.

From a time management standpoint, Order B, which was used for Round 3a devices, is preferred. The e-beam evaporation deposition tool can handle up to four wafers at one time, but the bonder can only process one pair of silicon and Pyrex wafers at one time. Thus, by depositing metal before bonding, four wafers can complete this step together immediately, whereas depositing later would either require waiting for four wafers to complete the KOH etching step, or (if producing a complete wafer set quickly is a priority) inefficiently using the evaporator by placing fewer than four wafers in the tool.
3.7. PROCESS DESIGN

However, Order A produces high quality devices. Depositing metal early in the fabrication process flow requires that layer to be protected throughout the remainder of the process flow, which can be challenging. During bonding, the wafer surface is covered with an electrode, which may scratch the metal if it has been deposited already. Thus, delaying metal deposition and patterning to the end of the process flow, as in Order A, creates more reliable resistors. For this reason, only Order A was used for full device fabrication starting with Round 3b.

3.7.2 Placement of insulating oxide growth step

The oxide layer that electrically insulates the metal resistors from the silicon diaphragm must be grown before the SOI and Pyrex wafers are bonded because Pyrex is not permitted in the MIT MTL atmospheric diffusion tubes where oxide is grown. It is possible for oxide growth to take place between KOH etching and wafer bonding. However, like metal deposition, oxide growth is done on a whole batch of wafers simultaneously. Since KOH etching is a half-day process and can only be performed on one wafer at a time, the user must either wait until several wafers have completed the KOH etch process before growing oxide or spend time performing separate oxide growth procedures for each wafer or group of wafers.

Thus, etching away the nitride from the front-side (leaving a protective nitride ring) and growing insulating oxide in its place should immediately follow the growth of the nitride layers.

3.7.3 Open access to cavities

Metal deposition occurs in a near-vacuum to reduce impurities in the atmosphere from depositing in the metal film. When a bonded wafer set, complete with flexible diaphragms and cavities, is placed inside the evaporator in accordance with Order A, the cavities must be open to the outside. If the cavities had instead been sealed under atmospheric pressure, the vacuum would cause the diaphragms to deform under the pressure difference, which can damage them.
Round 4 devices already have the snaking channel etched in the Pyrex that connects the cavities with the external environment. The Round 3b devices, however, have each column of diaphragms sharing an air channel, but the channels are otherwise isolated from the environment. To open the channels up, one diaphragm in each column is carefully broken after the wafers are bonded and before the bonded wafer set is placed in the evaporator.

3.7.4 Wet processing bonded wafers

A potential hurdle in assessing the viability of the process flow is how chemicals used in subsequent wet processing affect the bonded wafer, which has accessible air channels. The concern is that these chemicals would be stuck inside the air channels. Experiments demonstrated that wet etchants as varied as piranha, Cr-7 and gold etchant can be removed by repeatedly rinsing with water, spin drying, and post-baking.
3.8 Mask Design

3.8.1 List of masks

All masks except Mask R were drawn using Adobe Illustrator software, printed out on high-quality transparencies produced by PageWorks, and transferred to 7” glass-chromium masks. These masks have a minimum feature size of 5 µm. Mask R, which patterns the metal resistors, required higher resolution, as precise resistor dimensions and no breaks in the resistor path are critical for functional sensors. Therefore, Mask R was drawn using AutoCAD software and was directly laser-printed to a 7” glass-chromium mask by Advanced Reproductions. This mask has a minimum feature size of 0.1 µm. Appendix D presents all the masks used for all rounds of device fabrication:

- Mask P (Pyrex features)
- Mask N (finding the crystalline plane)
- Mask O (protective nitride ring)
- Mask M (alignment marks)
- Mask D (diaphragm)
- Mask R (resistors)

In the Round 3b and 4 process flow and mask designs, the features on Mark M were completely incorporated into Mask O, thus rendering Mark M superfluous. Additionally, as discussed in Section 3.2 and Subsection 3.4.2, Round 3b and 4 have no Mask N.

3.8.2 Mask alignment

Precise alignment is critical because the features on all the masks must be superimposed on one another for the devices to operate correctly. Figure 3-5 shows the alignment mechanism using EV1 in MTL TRL.

All masks have identical alignment marks placed at identical locations on the left and right sides. Each set of marks, shown in Figure 3-6, occupies a 2.5 mm × 2.5 mm area of
Figure 3-5: Two-sided alignment mechanism. The diagrams on the left-hand side show the side view of the mask, wafer, chuck and optical system, and the diagrams on the right-hand side show the view on the computer monitor. (a) The image of the mask alignment marks is read and projected on the computer monitor. (b) The alignment marks on the bottom-side of the wafer are also projected on the monitor. (c) The position of the wafer is adjusted by translation and rotation until the two images match acceptably well. Reproduced from [56].
space. Each set contains four 875 μm × 250 μm rectangles arranged in a cross. In the center of a cross, there is a much smaller cross made up of four 87.5 μm × 25 μm rectangles.

Two sets of alignment marks, one each from the left and right sides of the mask, are viewed simultaneously. Once the large crosses on the mask and the wafer are reasonably aligned, the magnification is increased to image and align the small crosses for fine positional and angular adjustment.

Each photolithography step requires mask alignment, though for different reasons and through different mechanisms. The first alignment is Mask P. Since the Pyrex wafer only has one set of features produced by one mask, and Pyrex etching is identical regardless of wafer orientation, Mask P only needs to be aligned so that the wafer flats of the Pyrex wafer and the SOI wafer roughly coincide after bonding, which makes physical handling easier. As can be seen in Appendix D, some masks have horizontal bars near the bottom with which the wafer flat can be aligned with the aid of optical instruments.

The second alignment is Mask M (Rounds 1 and 3a) or Mask O (Rounds 3b and 4) for
the SOI wafer. Since this mask forms the reference for all subsequent masks, aligning it properly is extremely important. As discussed in Subsection 3.4.2, Rounds 1 and 3a have an additional KOH etch step to find the crystalline plane (after which the alignment marks in Mask M are laid down), but Rounds 3b and 4 assume the crystalline plane is perfectly parallel to the wafer flat (and Mask O, which contains the alignment marks from Mask M, is laid down).

The third alignment is Mask D for the SOI wafer. Since Mask D is applied to the back-side of the SOI wafer and needs to be aligned to the features from Mask O, which are on the front-side, a special alignment mechanism is used. Mask D is inserted into EV1 and adjusted so that the optical sensors are focused on its alignment marks, which are locked onto the computer monitor. The wafer is placed back-side up into the chuck, and an image of the front-side wafer marks are superimposed on the computer monitor. The position of the wafer is then adjusted so that they match.

Finally, the fourth alignment is Mask R for the SOI wafer. This is simply placed so that its alignment marks are superimposed on those from Mask O.
Chapter 4

Measurements

This chapter discusses the measurements of the fabricated devices. Section 4.1 shows photographs of the devices. Section 4.2 describes the various instrumentation used to control applied pressure and make mechanical and electrical measurements. Section 4.3 compares measurements of the deflection of the center of diaphragm to the model described in Section 2.6. Section 4.4 explains how the origin of drifting signals was discovered and managed. Section 4.5 shows external bridge measurements from isolated sensors. Section 4.6 describes how underwater testing was done. Finally, Section 4.7 summarizes the results of the measurements.

Note: The pressure indicated by the manometer-controlled experiments is the added back-side pressure. This is the opposite of the convention discussed in Section 2.6.
CHAPTER 4. MEASUREMENTS

4.1 Photographs of Devices

Photographs of the devices are shown on the following pages. The left side of Figure 4-1 shows a device from Round 1 (silicon diaphragm without strain-gauge resistors). A manometer attached to the copper tube controls the air pressure in the cavity underneath the diaphragm. A scanning electron microscope (SEM) photograph of the diaphragm cross-section is on the right.

Figure 4-1: Device from Round 1 (silicon diaphragm without strain-gauge resistors). (Left) Device affixed to a standard 75 mm × 25 mm glass microscope slide. (Right) SEM photograph of the cross-section of a diaphragm. The white layer on the top is the silicon nitride mask (nominally 0.3 µm). The clouded layer on the bottom is the silicon oxide etch stop (nominally 1 µm).

The thickness of the diaphragm was measured to be 18.2 µm, about 10% thinner than the nominal 20 µm. Since the deflection and sensitivity are inversely proportional to the cube of the thickness, the thinner diaphragm would increase both by about 37%. This is an important observation when examining experimental deflections in Section 4.3.
4.1. PHOTOGRAPHS OF DEVICES

Figure 4-2 shows the entire wafer from Round 2 (strain-gauge resistors on dummy nitride wafer).

Figure 4-2: An entire wafer from Round 2 (strain-gauge resistors on dummy nitride wafer). The wafer is 150 mm in diameter. Each cell is 10 mm × 10 mm. Inset: Microscope photo of center portions of strain-gauge resistors. The narrow metal lines in the center are 10 µm wide.
Figure 4-3 shows an entire wafer from Round 3 (isolated strain-gauge sensors).

Figure 4-3: An entire wafer from Round 3 (isolated strain-gauge sensors). The wafer is 150 mm in diameter. Each cell is 10 mm × 10 mm.
Figure 4-4 shows both the front-side (top) and the back-side (bottom) of an entire wafer from Round 4 (interconnected sensors).

Figure 4-4: An entire wafer from Round 4 (interconnected sensors). Both the front-side (top) and the back-side (bottom) are shown. The wafer is 150 mm in diameter. The chromium/gold lines are conduction wires, strain-gauge resistors, and access pads. The horizontal lines as seen from the back-side are the air channels etched in Pyrex. The green color is the back-side nitride on the SOI wafer. Each indented blue $2 \text{ mm} \times 2 \text{ mm}$ square is the oxide on the underside of a silicon diaphragm.
4.2 Instrumentation

The various instrumentation used to control applied pressure and make mechanical and electrical measurements are described below.

4.2.1 Manometer

A manometer was used to control the pressure in the cavities of the devices from Rounds 1 and 3. Figure 4-5 shows a photograph of the manometer. A U-shaped plastic tube is half-filled with water. One end of the tube is open to the atmosphere. The other end forks to a syringe and a longer tube that connects to the copper tubes that lead to the sensor cavities. By moving the piston in the syringe, the air pressure in that portion of the U-tube changes, which pushes (higher pressure) or pulls (lower pressure) the water. The difference in the heights of the water between both sides of the U-tube, which is easily seen on the graph paper behind the tube, corresponds to the pressure difference across the two sides of the sensor diaphragm. Pressure differences between $-1500$ Pa and $1500$ Pa with a precision of $10$ Pa can be produced.
Figure 4-5: Manometer used to control the pressure in the cavities of devices from Rounds 1 and 3.
4.2.2 Zygo profilometer

A Zygo NewView™ 5000 optical interferometer was used as a desktop profilometer to measure the normal deflection of the entire surface of diaphragms under pressure to sub-angstrom vertical resolution. Because the machine takes several seconds to scan the surface to produce a single image, only static measurements are possible. Figure 4-6 shows a photograph of the Zygo profilometer.

Figure 4-6: Photograph of the Zygo profilometer.
4.2. INSTRUMENTATION

4.2.3 Off-wafer differential amplifiers

Differential amplifiers were built off-wafer to amplify the output of the sensors from Rounds 3 and 4. The circuit diagram is shown in Figure 4-7. The LM741 chip, powered by 9 V batteries, was used for all operational amplifiers. The circuit parameters were as follows:

\[
R_1 = 1.5 \, \text{k}\Omega, \quad GR_1 = 1.0 \, \text{M}\Omega, \quad (4.1)
\]
\[
R_2 = 10 \, \text{k}\Omega, \quad C_1 = 50 \, \text{nF}, \quad (4.2)
\]
\[
R_3 = 41 \, \Omega, \quad C_3 = 50 \, \text{nF}. \quad (4.3)
\]

The bridge source voltage \( V_s \) varied depending on the experiment. Note that the nominal gain \( G \) is around 666. The cut-off frequencies of the \( GR_1-C_1 \) and \( R_3-C_3 \) systems are 3 Hz and 77 kHz, respectively.

![Figure 4-7: Circuit diagram of off-wafer differential amplifier.](image-url)
The static and frequency responses of the three off-wafer differential amplifiers are shown in Figure 4-8. These circuits were built to test three individual strain-gauge resistors simultaneously. Since we are interested in changes in the bridge voltage as the pressure applied to the diaphragm is varied, the offsets in the static gains are not an issue. As explained in Subsection 4.4.1, a strain-gauge resistor is tested by placing it in a tunable external Wheatstone bridge, the output of which is fed into one of the differential amplifiers. The Wheatstone bridge is tuned so that the amplified output is close to zero. However, any offsets in the amplifier gain characteristics would only affect the tuning of the bridge. The change in the bridge voltage difference is still multiplied by the gain regardless of the offset.

Figure 4-8: Static response (top) of off-wafer differential amplifiers. The measured gains are 619, 624 and 576, respectively. The frequency response (middle and bottom) of one amplifier (Amp #2) is also shown.
4.2.4 Tech-Etch cable

A long, flexible and waterproof cabling system was needed to power and read outputs from the Round 4 devices. First, a flat cable custom-made by Tech-Etch was used to access the bridge pads on the Round 4 wafers. The Tech-Etch cable is a 22” long, 1.9” wide, and 0.031” thick waterproof flexible plastic cable with exposed tin-plated copper pads on one end (the head) that fit the bridge pads on the wafer one-to-one. Like the bridge pads, the copper pads are 0.1” × 0.1” and are spaced 0.1” apart. The other end (the tail) is a standard 50-pin D-sub connector, which can then be fed into a matching D-sub cable. The cable wires are individually addressed to access particular sensors on the wafer.

Figure E-4 in Appendix E depicts a technical diagram of the Tech-Etch cable. A photograph of the head with the copper pads is shown in Figure 4-9.

The cable worked as expected, though adding solder bumps to the tin-plated copper pads helped ensure contact between the cable and the wafer pads.

Figure 4-9: Photograph of the head of the Tech-Etch cable. It is 1.9” wide at the top and 3.9” wide at the bottom. The square pads are 0.1” × 0.1” and are spaced 0.1” apart.
4.2.5 Water-level probe

A resistive probe was used to measure water depth in real-time, which is part of the underwater testing for Round 4. The probe consists of two parallel conducting rods, each 320 mm long and 3 mm in diameter, spaced 4 mm apart. When the probe is partially submerged in a resistive fluid, such as water, the voltage output of the probe changes linearly in response to the amount of resistive fluid between the rods. Thus, assuming the fluid is homogeneous, the voltage changes linearly as the surface of the fluid moves relative to the probe, either by moving the probe into or out of the fluid or by the presence of surface waves in the fluid.

Figure 4-10 shows a photograph of the water-level probe. The probe is placed vertically into a bucket of distilled water. Figure 4-11 shows a calibration of the water-level probe, where the depth of the water at the tip of the probe has been converted to water pressure.

Figure 4-10: Photograph of the water-level probe (sideways). The bottom tip is at the right. The white plastic portion shown on the left waterproofs the probe electronics.
Figure 4-11: Voltage vs. pressure to calibrate the water-level probe. The sensitivity is 6.8 mV/Pa. The water depth has been converted to water pressure.
4.3 Deflection

In order to verify that a silicon diaphragm can serve as the basis of a pressure sensor, measurements of the deflection of the diaphragm against applied pressure are compared to the model described in Section 2.6.

First, the deflection of an entire diaphragm surface was measured with a Zygo profilometer for several Rounds 1 and 3 diaphragms at various pressures between $-1500$ Pa and $1500$ Pa with the back pressures controlled by the manometer. Figures 4-12 and 4-13 show the profiles of a $2828\,\mu$m diaphragm at $-1500$ Pa and $1500$ Pa, respectively.

![Profile of a 2828 µm diaphragm at a pressure of -1500 Pa as measured by a Zygo profilometer. Upper left: Color-coded contour graph. Upper right: 3-D plot (not to scale). Lower left: Profile of cross-section indicated by center horizontal line in upper left graph (not to scale). Note that the snaking resistor thickness is apparent and is as expected. Lower right: Optical photograph.](image)

Figure 4-12: Profiles of a 2828 µm diaphragm at a pressure of $-1500$ Pa as measured by a Zygo profilometer. Upper left: Color-coded contour graph. Upper right: 3-D plot (not to scale). Lower left: Profile of cross-section indicated by center horizontal line in upper left graph (not to scale). Note that the snaking resistor thickness is apparent and is as expected. Lower right: Optical photograph.
Figure 4-13: Profiles of a 2828 µm diaphragm at a pressure of +1500 Pa as measured by a Zygo profilometer. Upper left: Color-coded contour graph. Upper right: 3-D plot (not to scale). Lower left: Profile of cross-section indicated by center horizontal line in upper left graph (not to scale). Note that the snaking resistor thickness is apparent and is as expected. Lower right: Optical photograph.
Then, detailed measurements of the deflection at the center of the diaphragm ($c_1$) at various pressures ($P$) between $-1500$ Pa and $1500$ Pa for diaphragms of three different sizes were made. Figure 4-14 shows the results from two diaphragms of sizes $2000$ µm and $2828$ µm. Figure 4-15 shows the results from a $4000$ µm diaphragm. The slopes of the best-fit lines for the experimental data are given in Table 4.1, along with the theoretical relationship between $c_1$ and $P$ for various diaphragm lengths $L$ (all with thickness $H = 20$ µm) calculated in Section 2.10.

<table>
<thead>
<tr>
<th>Diaphragm Length (µm)</th>
<th>Theoretical $c_1/P$ (nm/Pa)</th>
<th>Experimental $c_1/P$ (nm/Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.0118</td>
<td>—</td>
</tr>
<tr>
<td>1414</td>
<td>0.0470</td>
<td>—</td>
</tr>
<tr>
<td>2000</td>
<td>0.188</td>
<td>0.381</td>
</tr>
<tr>
<td>2828</td>
<td>0.752</td>
<td>1.34</td>
</tr>
<tr>
<td>4000</td>
<td>3.01</td>
<td>8.97</td>
</tr>
</tbody>
</table>

Table 4.1: Slopes $c_1/P$ for various diaphragm lengths $L$.

The difference between theory and experiment could be the result of several phenomenon. For example, the silicon oxide grown and metal deposited on the diaphragm occurred under high temperature and low pressure, respectively. These processes could have pre-stressed the diaphragm layers to alter the deflection-pressure characteristics. Recall from Subsection 2.6.4 that the complete relationship between pressure ($P$) and center deflection ($c_1$) is

$$P = \left\{ C_r \left[ \frac{\sigma_0 H}{L^2} \right] + C_b \left[ \frac{EH^3}{(1-\nu^2)L^4} \right] \right\} c_1 + C_s f_s(\nu) \left[ \frac{EH}{(1-\nu)L^2} \right] c_1^3, \quad (4.4)$$

where $C_r$, $C_b$ and $C_s$ are constants, which refer to the residual stress, bending, and stretching terms, respectively; $\sigma_0$ is residual stress in the diaphragm; and $f_s(\nu)$ is a function of $\nu$. Since $c_1 \ll H$, the linear $c_1$ terms dominate over the cubic $c_1^3$ term. Thus, we obtain

$$P \approx \left\{ C_r \left[ \frac{\sigma_0 H}{L^2} \right] + C_b \left[ \frac{EH^3}{(1-\nu^2)L^4} \right] \right\} c_1. \quad (4.5)$$
Previously, we assumed there was no residual stress, \( \sigma_0 = 0 \). However, if \( \sigma_0 \) were a negative number, there would be a greater deflection for a given pressure. Let’s determine the stress necessary to increase \( c_1/P \) by a factor of 2, which occurs when the stress term is half of the opposite of the bending term:

\[
C_r \left[ \frac{\sigma_0 H}{L^2} \right] = -\frac{1}{2} C_b \left[ \frac{E H^3}{(1-\nu^2)L^4} \right].
\]  \hspace{1cm} (4.6)

We also showed earlier that \( C_b = 1/K_E = 1/(12k_D) = 1/(12 \times 0.00133) \approx 62.7 \). According to [73], a reasonable choice for \( C_r \) as calculated by energy methods is \( C_r = \frac{3\pi^2}{2} \). Using \( H = 20 \mu m, L = 2000 \mu m, E = 169 \) GPa and \( \nu = 0.064 \), Equation 4.6 produces the residual stress

\[
\sigma_0 = -36 \text{ MPa}. \hspace{1cm} (4.7)
\]

Such a value for compressive stress is typical in grown thin silicon oxide films [56, 73, 66]. There are two reasons for the stress. Silicon oxide molecules occupy more volume than silicon atoms, and there is a mismatch between the coefficients of thermal expansion of silicon and silicon oxide. However, since the compressive stress is dependent on several process parameters, including the pressure, temperature, rate, thickness, humidity and cooling, the exact value is difficult to control.

Second, since the deflection scales as the inverse of the cube of the diaphragm thickness, any slight overetching of the silicon, which thins the diaphragms, or a slightly thinner diaphragm as manufactured by the vendor, would have a comparatively large effect on the deflection. As discussed in Section 4.1, the thickness of one diaphragm was measured to be 18.2 \( \mu m \), about 10% thinner than the nominal 20 \( \mu m \). Since the deflection and sensitivity are inversely proportional to the cube of the thickness, the thinner diaphragm would increase both by about 37%.

Third, since the deflection scales as the fourth power of the diaphragm length, the actual diaphragm length may be larger than the nominal design value. The discrepancy
has several sources. As discussed in Section 3.4.2, devices from Rounds 3b and 4 assumed that the wafer flat was parallel to a (110) direction. If this is tilted by an angle, the KOH etch would expand the diaphragm to be bounded by the smallest (110)-bounded rectangle that contains the designed square. A one degree tilt would increase the length by about 1.7%. Next, as discussed in Section 2.6, we assumed the diaphragm is fixed to the cavity edges as an ideal boundary condition. However, in reality, part of the surface of the silicon immediately outside the diaphragm would be deflected as well, which increases the effective diaphragm length. The correction to the effective length is on the order of several thicknesses of the diaphragm. Since the \( L/H = 100 \) for the \( L = 2000 \mu m \) diaphragms, this could contribute a few percent to the additional flexibility of the diaphragm. Finally, as discussed in Section 3.4, the walls of the KOH cavities produced form 54.7° angles with the surface plane. Thus, the nitride mask windows need to be larger than the designed diaphragm size where each window side is moved outwards by \( x = T \cot 54.7° \), where \( T \) is the handle wafer thickness. This was taken into account when the back-side mask for the diaphragm windows, Mask D, was created. However, if the actual value of \( T \) is smaller than the nominal value, which was used in mask design, then the diaphragms will be larger than intended. For every 15 µm the actual handle wafer thickness is smaller than the nominal value, the length of the diaphragm increases by 1%.

All of the phenomena discussed above contribute to greater deflection for a given applied pressure. In any case, the diaphragms are more sensitive than they were designed to be. Furthermore, they display consistent results over long periods of time and have no hysteretic effects, which means they can be reliably calibrated as pressure sensors.

Note that the 4000 µm diaphragm is flexible enough that the center deflection is no longer linear with pressure in the −1500 to 1500 Pa range. As discussed earlier in Subsection 2.6.4 and Section 2.10, linearity is only assumed when the deflection of that diaphragm is less than 10% of the diaphragm thickness, which for the 4000 µm diaphragm, restricts absolute pressure differences to less than 664 Pa. Regardless, nonlinearity is an acceptable characteristic for a pressure sensor. Like the smaller diaphragms, the nonlinearity of the large diaphragm is consistent over time and thus can be calibrated.
4.3. DEFLECTION

Figure 4-14: The deflection of the center of the diaphragm at various pressures for two different sizes. The circles and stars represent data points and the solid lines represent the best-fit lines. The shallow plot (blue line, black circles) results from a 2000 \( \mu \text{m} \) diaphragm, and the steep plot (green line, black stars) results from a 2828 \( \mu \text{m} \) diaphragm. The slopes of the best-fit lines are 0.381 nm/Pa and 1.34 nm/Pa, respectively.
Figure 4-15: The deflection of the center of the diaphragm at various pressures for a 4000 µm diaphragm. The circles represent data points and the solid line represents the best-fit line. The slope of the best-fit line is 8.97 nm/Pa.
4.4 Drifting Signals

After the diaphragms were confirmed to mechanically deflect in response to pressure, electrical measurements of the sensors were made. The resistances of the strain-gauge resistors across a Round 3 wafer ranged from 15 kΩ to 18 kΩ. The monotonic gradient in resistance change as one sweeps across the wafer is likely due to a gradient in metal thickness during e-beam deposition, which is typical. Then, the output of Wheatstone bridges made of external resistors and individual strain-gauge resistors were tested as applied pressure was varied. However, contact resistance between the chromium resistor pads and microscope probes was found to be unstable, and steps were taken to stabilize it. This experience led to the addition of gold on the chromium pads for the fabrication of Round 4 devices. This series of experiments is discussed in below.

4.4.1 Experimental set up

A pair of microscope probes were pressed on the pads of a strain-gauge resistor to enable connection to an external, well-characterized circuit. A Wheatstone bridge was set up off-wafer using two fixed resistors, one variable resistor in the form of two potentiometers in series, and one device strain-gauge resistor. The fixed resistors were selected to approximately match the expected resistance of the strain gauge. The output of the quarter bridge is then fed into the differential amplifier described in Subsection 4.2.3. Two potentiometers, one much larger than the other, were used in series to allow for coarse and fine tuning. The potentiometers are adjusted until the bridge measures close to zero output for zero input, which is a highly delicate procedure. This experimental set up is depicted in Figure 4-16.

The amplified output of an external bridge testing a single resistor on a 4000 μm diaphragm at zero applied pressure was measured over an 80-second period. Figure 4-17 shows raw (blue) and time-averaged (green) traces. The signal slowly drifts over the course of the 80-second period. This effect was consistently observed for all resistors tested.
4.4.2 Dummy bridge

To determine whether the drifting effect was specific to the wafer devices or had an external explanation, the output of a dummy bridge consisting solely of standard resistors and potentiometers was observed with the same amplification circuitry and physical wiring that the strain-gauge resistor had. The amplified output was observed to be stable. Thus, the drifting signal effect originated from the devices. The following hypotheses were made to explain the phenomenon, all of which were investigated. Eventually, unstable contact resistance was found to be the cause.

1. E&M interference;

2. Fluctuating pressure;

3. Unstable contact resistance.

4.4.3 E&M interference

It is possible that the strain-gauge resistors and/or the silicon wafer were acting as an antenna and the AC electromagnetic signals they received were being rectified by the amplifier circuit as a DC signal. However, remedies such as adding inductive cores around the wires, adding lowpass filters in front of each amplifier, grounding the silicon wafers, and Faraday
shielding all had no effect, all of which indicate that the drifting phenomenon is internal to the wafer.

4.4.4 Fluctuating pressure

If the applied pressure on diaphragm were changing slowly on a small scale, then the trace seen reflects a true pressure signal. Resistors on the same diaphragm would then respond together. However, this was not the case: The outputs appear to be uncorrelated and had different amplitudes. Furthermore, the deflection of the diaphragm would fluctuate as well. However, real-time observation of the diaphragm under the Zygo interferometer confirmed that the diaphragm was not moving, at least not on the nanometer scale that the observed
change would require.\footnote{Although it takes several seconds for the Zygo to take a complete profile measurement, the microscope on the Zygo allows the user to see optical interference patterns on a surface in real time. Any nanometer-scale changes would be immediately observed.}

### 4.4.5 Unstable contact resistance

The strain-gauge resistors are being accessed by microscope probe needles pressed into the resistor pads. The pads consist of thin ($2000 \, \text{Å}$) film chromium, plus some native chromium oxide on the exposed surface. To access the chromium, the probe needle is carefully but firmly scratched into the film by precision-tuning the probe arm. If the contact resistance between the probe needles and the chromium pads fluctuates, the output of the bridge would fluctuate.

To test this hypothesis, a dummy bridge consisting solely of standard resistors and potentiometers, like the one earlier, was set up. However, the path between two dummy resistors was routed to two microscope probes pressed against the same chromium pad. A drifting signal similar to the trace in Figure 4-17 appeared. Since the only difference between this arrangement and the dummy bridge described in 4.4.2 is the path through the chromium pad, the experiments prove that a fluctuating contact resistance between the microscope probe needles and chromium pads is the source of the drifting bridge signal.

### 4.4.6 Stabilizing the contact resistance

Several approaches were pursued to stabilize the fluctuating contact resistance. Because the resistor pads are coated with a thin chromium oxide, all required scratching or wet etching with KOH to remove a portion of it. First, wire-bonding 50-µm gold wires onto the pads was attempted. Since gold does not adhere to the pads directly due to the presence of chromium oxide, a conducting epoxy is necessary, even after scratching away the oxide. This method successfully accessed the chromium pads, but the gold wires were extremely delicate and the procedure is difficult to replicate reliably for several pads without the wires eventually falling off from the weak connections. Next, copper magnet wire, which is thicker and stronger than the gold wires, was attempted. Because of its weight, a combination of
4.4. **DRIFTING SIGNALS**

CircuitWorks® conductive silver epoxy (to affix wires to the Cr pads) and LOCTITE® Fixmaster fast cure epoxy (to provide mechanical support) was required to achieve a stable connection to the resistors. Like the gold wires, a successful electrical connection is made, but the wires eventually lose contact with the pads.

Finally, the microscope probe needles were permanently affixed into the pads with both conducting and mechanical epoxy. The process is as follows:

1. Clip two 3 mm tips from the microscope probe needles.
2. Use precision probe holders to place the tips on the two chromium pads of one strain-gauge resistor.
3. Apply KOH as a wet etch to dissolve the thin chromium oxide film.
4. Add conducting epoxy around the contact point.
5. Wait at least 4 hours for the conducting epoxy to harden.
6. Add mechanical epoxy around the entire pair of pads.
7. Wait at least 12 hours for the mechanical epoxy to harden.
8. Carefully unscrew the tips from the probe holders.
9. Solder the wires to the tips.
10. Add waterproofing (either Parylene or rubber cement).

During epoxy hardening, probe tips must be held in place, but the support must be able to be removed without releasing stress. A photograph of the result is shown in Figure 4-18.

Unfortunately, the tips eventually lost contact with the pads. It is believed that the regular epoxy does not grip the metal probe needle tips tightly enough. Thus, another mechanical epoxy, WEST SYSTEM®, was tested.\(^2\) This was found to work best; the

\(^2\)The specific WEST SYSTEM® epoxy used is a marine-grade epoxy consisting of three components: (1) the 105 Epoxy Resin®, a low-viscosity liquid epoxy resin that does not shrink after curing; (2) the 205 Fast Hardener®, a medium-viscosity epoxy curing agent; and (3) the 403 Microfibers®, a fine fiber blend used as a thickening additive.
probe needle tips were held in place. Another advantage to this epoxy is that the final epoxy vertical profile is much lower, which allows the use of smaller probe needle tips. Since the risk of mechanical failure is greater for large tips, this is a helpful side effect. However, this epoxy is less viscous than most epoxies and glues, so during the hardening period, the diaphragms are covered with liftoff cardboard to protect them from liquid epoxy.

Figure 4-19 shows a side view of several resistors accessed with the new epoxy and microscope probe needle tips. Figure 4-20 shows both types of epoxies.

Figure 4-19: Contact resistance stabilized by WEST SYSTEM® epoxy and microscope probe needle tips.
4.4. DRIFTING SIGNALS

Figure 4-20: Contact resistance stabilized by both types of mechanical epoxies and microscope probe needle tips.

One downside to the epoxy is that heat from a soldering iron used on the probe needle tips softens the epoxy, which loosens the tips. Thus, any wires must either be soldered to the tips before the tips are epoxied to pads or are carefully clipped to the tips.

Even after the contact had been stabilized, only about half of the drifting phenomenon was removed. The other half is likely due to micro-cracks in the resistors.

4.4.7 Gold on chromium

The chromium oxide that grows once the chromium film is exposed to air makes the resistor contacts difficult to access. This problem is prevented in subsequent devices by the addition of a gold deposition step immediately following the chromium deposition under the same vacuum. Not only is gold inert in air, but it serves as an excellent conductor for external probes. However, the high conductivity of gold also requires the film to be much thinner than the chromium film so that the gold does not significantly reduce the total resistance of the strain-gauge resistors. Thus, as discussed in Section 3.2, whereas devices from Rounds 1, 2, 3a and 3b have only chromium as the resistor material, Round 4 devices have a gold-on-chromium (Au-on-Cr) double-layer metal film as the resistors.
4.5 External Bridge Measurements from Isolated Sensors

After the contact resistance between the microscope probe needle tips and the strain-gauge resistor pads had been stabilized, the isolated strain-gauge resistors of the Round 3b devices are tested. Like the experimental set up described in Subsection 4.4.1, the strain-gauge resistors are individually tested by placing each in an external Wheatstone bridge, where the other three Wheatstone components are fixed resistors and potentiometers. The bridge output is amplified by the differential amplifier described in Subsection 4.2.3. As before, the potentiometers were fine-tuned to set the output voltage to be as close to zero as possible when no pressure is applied to the diaphragms.

The manometer described in Subsection 4.2.1 is attached to the copper tubes on the wafer, which enables the experimenter to control the back pressure on a column of sensors. Since the manometer is water-based, the range and resolution of differential pressure between atmospheric pressure on the top of the diaphragms and the back pressure on the bottom is determined by the size of the manometer. We can produce pressure differences between $-1500 \text{ Pa}$ and $1500 \text{ Pa}$ with a precision of $10 \text{ Pa}$.

Figure 4-21 shows the output of an external bridge from a 4000 $\mu$m diaphragm undergoing $\pm 1600 \text{ Pa}$ changes. The source voltage is 21.9 V and the amplifier gain is 660. Figure 4-22 shows the output from the same system, but with $\pm 200 \text{ Pa}$ changes. Finally, Figure 4-23 shows the output from a single 200 Pa step. Note that the slow time response, as evidenced by a first-order time constant of around 1 s, is due to the pressure tubes and the amplifier circuits, not the sensors themselves. As expected, the outputs respond to pressure change.
4.5. *EXTERNAL BRIDGE MEASUREMENTS FROM ISOLATED SENSORS*

Figure 4-21: The output of an external bridge from a 4000 µm diaphragm undergoing ±1600 Pa changes (blue). The source voltage is 21.9 V and the amplifier gain is 660. The input pressure signal is overlaid (red).
Figure 4-22: The output of an external bridge from a 4000 \( \mu \text{m} \) diaphragm undergoing \( \pm 200 \) Pa changes (blue). The source voltage is 21.9 V and the amplifier gain is 660. The input pressure signal is overlaid (red).
Figure 4.23: The output of an external bridge from a 4000 μm diaphragm undergoing a 200 Pa step (blue). The source voltage is 21.9 V and the amplifier gain is 660. The input pressure signal is overlaid (red).
Next, the output of the amplifiers for various strain-gauge resistors is measured as the back pressure produced by the manometer is varied. Figures 4-24-4-28 show the measurements for resistors on five diaphragms, ranging from 2000 µm to 4000 µm in size. The notation “RxCy” refers to the row and column numbers of the diaphragm. The notation “UpRi”, “LoRi”, “LoLe” and “UpLe” are shorthand for “upper right”, “lower right”, “lower left” and “upper left”, respectively, which refer to the position of the resistor pads of a particular resistor relative to the rest of the cell, as shown in Figure 2-5 on Page 47.

Figure 4-24: External bridge voltage vs. pressure for various resistors from a 4000 µm diaphragm. The source voltage is 21.9 V. The amplifier gains are 619 and 624. Although the negative and positive pressure regions have different slopes, an average slope is computed from the best-fit lines: −4.72 mV/Pa (blue stars) and +4.67 mV/Pa (green triangles). Note that the relative slopes of the two regions are consistent with the asymmetry in the slopes seen in the −1200 Pa to +600 Pa range in the deflection measurements of the same diaphragm (Figure 4-15).
Figure 4-25: External bridge voltage vs. pressure for various resistors from a 2828 µm diaphragm. The source voltage is 20.2 V. The amplifier gains are 619, 624 and 576. The slopes of the best-fit lines are +1.51 mV/Pa (black circles), −1.61 mV/Pa (blue stars) and +1.56 mV/Pa (green triangles).
Figure 4-26: External bridge voltage vs. pressure for various resistors from another 2828 µm diaphragm. The source voltage is 20.2 V. The amplifier gain are 619, 624 and 576. The slopes of the best-fit lines are +2.06 mV/Pa (black circles), −1.62 mV/Pa (blue stars) and +1.68 mV/Pa (green triangles).
4.5. EXTERNAL BRIDGE MEASUREMENTS FROM ISOLATED SENSORS

Figure 4-27: External bridge voltage vs. pressure for various resistors from a 2000 μm diaphragm. The source voltage is 21.9 V. The amplifier gains are 619, 624 and 576. The slopes of the best-fit lines are +0.799 mV/Pa (black circles), −0.715 mV/Pa (blue stars) and +0.761 mV/Pa (green triangles).
Figure 4-28: External bridge voltage vs. pressure for various resistors from another 2000 μm diaphragm. The source voltage is 21.9 V. The amplifier gains are 619, 624, 576 and 619. The slopes of the best-fit lines are +0.841 mV/Pa (black circles), −0.833 mV/Pa (blue stars), +0.739 mV/Pa (green triangles) and −0.807 mV/Pa (red dots).
The slopes of the best-line fits are summarized in Table 4.2.

<table>
<thead>
<tr>
<th>Diaphragm</th>
<th>Resistor Location</th>
<th>Length (µm)</th>
<th>UpRi</th>
<th>LoRi</th>
<th>LoLe</th>
<th>UpLe</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2C8</td>
<td></td>
<td>4000</td>
<td>—</td>
<td>—</td>
<td>+4.67</td>
<td>—</td>
</tr>
<tr>
<td>R3C8</td>
<td></td>
<td>2828</td>
<td>+1.51</td>
<td>−1.61</td>
<td>+1.56</td>
<td>—</td>
</tr>
<tr>
<td>R4C8</td>
<td></td>
<td>2828</td>
<td>+2.06</td>
<td>−1.62</td>
<td>+1.68</td>
<td>—</td>
</tr>
<tr>
<td>R5C8</td>
<td></td>
<td>2000</td>
<td>+0.799</td>
<td>−0.715</td>
<td>+0.761</td>
<td>—</td>
</tr>
<tr>
<td>R6C8</td>
<td></td>
<td>2000</td>
<td>+0.841</td>
<td>−0.833</td>
<td>+0.739</td>
<td>−0.807</td>
</tr>
</tbody>
</table>

Table 4.2: Experimental values of slopes of best-fit lines for amplified voltage vs. pressure for strain-gauge resistors on various diaphragms from Round 3b. Units are mV/Pa.

Note, however, that the voltage-pressure relationship for the 4000 µm diaphragm is not linear, so the values above represent average slopes computed from the best-fit lines. One possible reason for the nonlinearity is asymmetric plastic deformation in the diaphragm.

The theoretical values for these slopes are shown in Table 4.3. These are calculated by adjusting the expected sensitivities from Section 2.10 (which assume a source voltage of $V_s = 10$ V and full bridge of strain-gauge resistors) by the actual source voltages, amplifier gains, and the fact that only quarter bridges are being tested.

<table>
<thead>
<tr>
<th>Diaphragm</th>
<th>Resistor Location</th>
<th>Length (µm)</th>
<th>UpRi</th>
<th>LoRi</th>
<th>LoLe</th>
<th>UpLe</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2C8</td>
<td></td>
<td>4000</td>
<td>—</td>
<td>−0.118</td>
<td>+0.119</td>
<td>—</td>
</tr>
<tr>
<td>R3C8</td>
<td></td>
<td>2828</td>
<td>+0.0539</td>
<td>−0.0545</td>
<td>+0.0503</td>
<td>—</td>
</tr>
<tr>
<td>R4C8</td>
<td></td>
<td>2828</td>
<td>+0.0539</td>
<td>−0.0545</td>
<td>+0.0503</td>
<td>—</td>
</tr>
<tr>
<td>R5C8</td>
<td></td>
<td>2000</td>
<td>+0.0295</td>
<td>−0.0297</td>
<td>+0.0274</td>
<td>—</td>
</tr>
<tr>
<td>R6C8</td>
<td></td>
<td>2000</td>
<td>+0.0295</td>
<td>−0.0297</td>
<td>+0.0274</td>
<td>−0.0295</td>
</tr>
</tbody>
</table>

Table 4.3: Theoretical values of slopes of best-fit lines for amplified voltage vs. pressure for strain-gauge resistors on various diaphragms from Round 3b. Units are mV/Pa.

Note that the strain-gauge resistors are more than an order of magnitude more sensitive than estimated. There are several possible explanations for the discrepancy between theory and experiment. Since the behavior of the strain gauges is related to the mechanical behav-
ior, the explanations mentioned in the Section 4.3 regarding the deflection measurements apply here as well:

- Oxide grown and metal deposited on the diaphragm may have pre-stressed the diaphragms;
- Overetching the silicon device layer may have thinned the diaphragms;
- The actual diaphragm lengths may be longer and wider than the nominal design values.

One other explanation could account for the remainder. The metal films that form the resistors may have micro-cracks from the diaphragm deflecting or other sources. These cracks consist of metal surfaces in contact with one another. Not only would resistance be concentrated at these points, but the local resistance there would be extremely sensitive to the relative motion of the surfaces. As the diaphragm deflects, more or fewer of the cracks come into contact, which is manifested in the changes in the resistance of the total strain-gauge resistor as a continuous phenomenon.

In any case, the sensitivity of the sensor is better than we had designed them to be. Importantly, the results are consistent and do not change over time, which means the pressure sensor can be calibrated. After taking the amplification, the 21.9 V source voltage, and the use of a quarter Wheatstone bridge into account, the sensitivity of a full bridge sensor on a 2000 $\mu m$ diaphragm powered by a 10 V source ranges from 2.1 to 2.5 $\mu V/Pa$, which is greater than the 0.087 $\mu V/Pa$ expected by the device model (Sections 2.6 and 2.10), and less than the 19.0 $\mu V/Pa$ achieved by a physically comparable standard piezoresistive pressure sensor (Section 2.5). With a noise level of 0.13 $\mu V$ (Section 2.10), the sensor can achieve sub-pascal resolution after appropriate mechanical and digital filtering is performed on pressure signals.
4.6 Underwater Testing

After the isolated strain-gauge resistors on the Round 3 devices were confirmed to respond to pressure applied to the diaphragm, Round 4 devices, where the strain-gauge resistors are wired together in Wheatstone bridges on the wafer, were fabricated. To make them suitable for underwater testing, the Round 4 wafers are mounted into a custom-made plastic holder, built with a recess for the wafer so that the top surface of the wafer is in-plane with the surface of the holder. The edges of the holder are also beveled to lower the wake profile. Thus, for future dynamic tests or measuring real pressure signals underwater, the edge of the wafer would not create large wakes that disturb the desired signal. The Tech-Etch cable described in Subsection 4.2.4 is placed on the wafer with the corresponding pads touching one-to-one. The cable is surrounded by waferproofing gel. A plastic plate locks it in place. Figure 4-29 shows a photograph of a Round 4 wafer with the Tech-Etch cable mounted in a wafer holder.

Figure 4-29: Photograph of a mounted wafer with pressure sensors that can be used underwater (Round 4). The wafer is 150 mm in diameter.
4.6.1 Out-of-water tests

First, the sensors from Round 4 were tested out of the water to check whether they respond to applied pressure. As with the Round 3 devices, the output of the bridges are amplified with the differential amplifier circuit described in Subsection 4.2.3. An air gun was slowly swiped across the wafer. The traces from two pressure sensors 2 cm apart on a Round 4 wafer was then recorded (Figure 4-30). The sharp spikes confirm that the sensors respond to applied pressure.

Figure 4-30: Sample trace of two pressure sensors 2 cm apart (Round 4) activated by air gun swiped across wafer.
4.6. UNDERWATER TESTING

4.6.2 Bucket tests

Next, the mounted wafer was placed vertically in a bucket of water, as shown in Figure 4-31.

![Bucket set up.](image)

Figure 4-31: Bucket set up.

To understand the dynamics of the water in the bucket, small waves were generated by a paddle. After the stimulus was removed, the water level at one particular location in the bucket was measured using the water-level probe described in Subsection 4.2.5 over a course of 10 seconds as the waves settled down. The resulting wave is shown in Figure 4-32.

The bucket waves have an amplitude of around 200 Pa, which corresponds to 20 mm of water pressure, the approximate observed height of the surface waves, as well as clear resonant characteristics. The experiment demonstrates that the dynamics of the water in the bucket appear straightforward enough to understand for the purposes of conducting tests with nominally static water; any components of the pressure signal at the resonant frequency of the bucket can be digitally filtered.

Full static testing of the Round 4 devices is to be performed as future work.
Figure 4-32: Resonant bucket waves. The pressure readings were calibrated from the water-level probe (see calibration from Figure 4-10).
4.7 Summary of Measurements

The results of the experiments in this chapter is summarized as follows.

Both the deflection and strain-gauge resistance measurements indicated that the sensor is more sensitive than the designed nominal values. The factor of 2 to 3 in the deflection can be attributed to several sources (Section 4.3):

- Compressive stress on the grown insulating silicon oxide film;
- Overetching of the diaphragm thickness;
- Angular misalignment of the devices features with the crystalline plane;
- The assumption of ideal clamping at the edges of the diaphragm;
- Manufacturing variation in the thickness of the handle wafer.

The compressive stress is by far the greatest effect, and could by itself account for all of the discrepancy between the model described in Section 2.6 and the experiments in this chapter. The overetching of the diaphragm could alter the deflection by about 37%. Finally, each of the other factors could contribute a few percent to the deflection as well.

The strain-gauge resistance measurements were, in turn, more sensitive than the deflection model would indicate, even after taking the factors above into account (Section 4.5). Micro-cracks in the resistors, which appear with bending thin metal films, could account for this remaining difference. A full bridge sensor on a 2000 µm diaphragm powered by a 10 V source has a sensitivity of 2.1 to 2.5 µV/Pa in the −2000 to 2000 Pa pressure range. With a noise level of 0.13 µV (Section 2.10), the sensor can achieve sub-pascal resolution after appropriate mechanical and digital filtering is performed on pressure signals.

Due to the existence of native chromium oxide, it is difficult to maintain a stable contact resistance between external microscope probe tips and thin chromium pads (Section 4.4). While the contact resistance can be stabilized with electrical and mechanical epoxies, the process is time-consuming and may not be permanent. Thus, Round 4 devices, gold was deposited on the chromium film under the same deposition vacuum to create a reliable inert contact.
Finally, preliminary tests with Round 4 devices indicated that sensors consisting of strain-gauge resistors wired up on-wafer powered by wafer-level conduction lines do indeed respond to changes in local external pressure (Section 4.6). Analysis of the surface waves in a small bucket of water showed that the dynamics of the waves can be filtered from pressure signals produced by underwater sensors to confirm their operation in nominally static water.
Chapter 5

Concluding Remarks

This chapter consists of three parts. Section 5.1 summarizes the results of this thesis, including lessons learned from the design, fabrication and testing of the strain-gauge pressure sensors. Section 5.2 discusses the contributions and conclusions made by this thesis in the areas of literature review, development of experimental techniques, fabrication and packaging observations, and MEMS applications. Finally, Section 5.3 suggests several directions for future work and explains how weaknesses can be addressed, such as improving the strain-gauge resign, adding an integrated amplifier and array read-out circuit to the devices, and fabricating pressure sensors using flexible materials.
5.1 Summary

This thesis presented the design, fabrication and testing of a high-density array of microelectromechanical systems (MEMS) pressure sensors inspired by the fish lateral line to enable passive navigation by autonomous undersea vehicles (AUVs). We demonstrated the feasibility of using a strain-gauge resistive silicon pressure sensor system with the device performance parameters necessary to measure pressure signatures that enable signal processing software on an AUV to detect and identify nearby objects (Chapter 1). While the devices were implemented in silicon, all the technology used is transferrable to flexible materials, such as polymers, which enables future generations of devices to be placed flush against the curved surfaces, such as fins and hulls. For this reason, pressure sensors using the piezoresistive properties of silicon were not considered.

Several rounds of devices were designed to test various combinations of device features (Chapter 2), including a diaphragm that deflects in response to pressure, resistors that act as strain gauges in response to the mechanical strain on the diaphragm, and air channels that connect the diaphragm cavities to the environment to remove the large-signal component of pressure change. A mechanical model of the diaphragm based on Kirchhoff-Love plate theory was developed to aid the design of the strain-gauge resistors that form the basis of the pressure sensor system and to characterize the dynamic response of the sensor. The designed performance parameters exceeded those required by AUV navigation.

The various rounds of devices were fabricated using standard integrated circuit (IC) technologies (Chapter 3). Techniques for etching silicon using potassium hydroxide (KOH) and etching Pyrex glass using solutions based on hydrofluoric acid (HF) were developed. The design issues in the material selection, process flow, and mask layout were explored and resolved.

Finally, the strain-gauge pressure sensors were tested (Chapter 4). We showed that square silicon diaphragms of sizes between 1000 µm and 4000 µm with thickness 20 µm can act as pressure sensors with the range and sensitivity required for underwater object detection. Although compressive stress on grown thin oxide films, over-etching of the diaphragms, simplifications in modeling the diaphragm length, and micro-cracks in the strain-gauge re-
sistors may have increased sensitivity, the behavior of deflection and resistors are consistent over time and display no hysteretic effects, which means that the system can be reliably calibrated. Preliminary tests verified that the strain-gauge pressure sensor system can be successfully tested and used underwater.
5.2 Contributions and Conclusions

In the course of the theoretical and experimental work that culminated in this thesis, research was conducted in several areas. The contributions of this thesis are as follows.

- A literature review of published work on:
  - The fish lateral line organ and biomimetics (Section 1.1);
  - MEMS pressure sensors (Section 1.2);
  - The small-deflection behavior of thin square diaphragms (Section 2.6);
  - Pyrex etching (Section 3.5);
  - The anisotropy of silicon as it relates to mechanical elasticity and etching (Sections 2.3, 2.6 and 3.4).

- The development of experimental techniques for:
  - KOH-etching one side of a silicon wafer (Section 3.4);
  - Etching Pyrex protected with a chromium/gold mask using an HF-based solution (Section 3.5).

- Fabrication and packaging observations:
  - KOH-etching a silicon wafer more than once, especially if one of the etches envelopes the entire wafer, renders the wafer physically fragile and prone to breaking in subsequent fabrication steps (Section 3.4).
  - It is possible to anodically bond silicon and Pyrex wafers through a 3000 Å layer of silicon nitride (Section 3.6). Even though the silicon has been etched by KOH and the Pyrex has been etched by an HF-based etchant, there are few enough pinholes that air-tight seals can be formed.
  - Removing silicon nitride using hot phosphoric acid is a thermally stressful procedure and should be avoided if possible (Section 3.6).
5.2. CONTRIBUTIONS AND CONCLUSIONS

– It is difficult to make stable electrical contacts with chromium pads due to the presence of a thin chromium oxide layer that grows on the pads upon exposure to air (Section 4.4). Thus, chromium deposition should be immediately followed by gold deposition under the same vacuum. Not only is gold inert in air, but it serves as an excellent conductor for external probes.

– Parylene can waterproof and insulate metal resistors (Section 4.6).

• Achieved pressure sensor specifications:
  – Millimeter-scale spacing;
  – Sensitivity of 2.1 to 2.5 µV/Pa (before amplification);
  – Sub-pascal pressure resolution;

• MEMS applications:
  – Created wafer-sized air channels for back pressure equilibration;
  – Developed a novel strain-gauge resistor design;
  – Successfully constructed a wafer-sized MEMS sensor system;
  – Demonstrated the feasibility of using a strain-gauge pressure sensor for underwater navigation applications;
  – Motivated research in techniques for developing flexible polymer pressure sensors.
5.3 Future Work

There are several directions that future work on the pressure sensors described in this thesis may take. From the short- to long-term, they are as follows.

- Further testing of Round 4 devices (fully interconnected strain-gauge sensors without amplifying transistors);
- Improved strain-gauge design;
- Integrated amplifier and array read-out circuitry;
- Printed electronics on flexible substrates.

5.3.1 Further testing of Round 4 devices

To complete the characterization of Round 4 devices (fully interconnected strain-gauge sensors without amplifying transistors), several tests are to be performed:

- Measure the static response of several sensors as the wafer is lowered, raised and tilted in water with the air channel plugged;
- Repeat static tests with air channel open to the water environment to test the large-signal filter;
- Measure the frequency response of several sensors using a hydrophone producing sinusoidal waves of single frequencies;
- Obtain pressure signatures of moving objects passing a stationary sensor in stationary water, stationary objects passing a moving sensor in stationary water, and stationary objects near a stationary sensor in a constant flow.

5.3.2 Improved strain-gauge design

The strain-gauge resistors described in this thesis have the following characteristics (Section 2.7):
5.3. **FUTURE WORK**

- Alignment along the directions parallel and perpendicular to the diaphragm edges;

- 10-µm wide cross-sections on the sensitive parts of the diaphragm;

- The strain-gauge resistor and conduction lines were fabricated from the same metal film.

Each characteristic suggests ways in which the strain-gauge design can be improved. To simplify the resistor design, the lengths of local sections of the strain gauges of the current devices are constrained to be aligned along the directions parallel and perpendicular to the diaphragm edges. By allowing the resistor sections to take arbitrary directions, a slightly more optimal set of resistors can be created.

Second, the narrowest resistor widths on 2000 µm diaphragms were 10 µm. This was a conservative specification to ensure that the long resistors did not have breaks. Since no photolithographic breaks were observed, the resistors can be made narrower, perhaps down to 2 or 3 µm. With a photolithographic resolution of 1 µm (Section 3.3), the facilities of the MIT Microsystems Technology Laboratories (MTL) where fabrication took place would be able to achieve this. Narrower resistor lines enables longer resistors to be created. As discussed in Section 2.7, both these effects contribute to larger resistances, which reduces the voltage drop across conduction lines on the surface of the Round 4 wafers that power the bridges.

Third, the strain-gauge resistor and conduction lines were fabricated from the same metal film. If an extra metalization step were to take place, it could thicken only the conduction lines by inserting a shadow mask over the strain-gauge resistors, thus reducing the conduction resistances. Like narrowing the strain gauges described earlier, this would have the effect of reducing voltage drop across the conduction lines.

All these ideas simply improve the sensitivity of the pressure sensor without addressing other performance characteristics. Since the sensitivity is already sufficiently high, design and fabrication efforts should be focused in other directions instead.
5.3.3 Integrated amplifier and array read-out circuitry

While the implemented version of the strain-gauge pressure sensor array system has off-wafer single-stage differential amplifiers to handle the signal processing, integrated circuitry is possible as well. The use of integrated circuits offers a significant signal-to-noise-ratio improvement with limited microfabrication complexity and low risk. In addition, the use of such an amplifier can greatly reduce the number of interconnects necessary to bring signals to and from each cell in the pressure-sensing array. We propose the following integrated circuitry that functions as both signal amplification and an array read-out system.

To minimize the wiring to a two-dimensional array of pressure-sensing cells, there is a set of wires such that each cell along a common column shares a common wire. Similarly, each cell along a common row shares an output wire. When a signal is sent to address a particular column, the output wires return the outputs from all the cells in that column. Thus, for an \( M \times N \) array of pressure-sensing cells, the number of interconnects scales as \( M + N \), rather than as \( M \times N \). Figure 5-1 depicts this concept.

![Figure 5-1: Interconnect wiring of an array of pressure-sensing cells.](image)

This addressing scheme can be implemented in the following manner. Each pressure sensor cell has a set of three metal-oxide-semiconductor field-effect transistors (MOSFETs)
5.3. **FUTURE WORK**

arranged as shown in Figure 5-2, a schematic of the integrated transistor amplifier and array read-out circuitry for a $2 \times 2$ array. Figure 5-3 shows the physical layout of one cell of the array. The cell is 10 mm $\times$ 10 mm. The diaphragm, indicated by the red square boundary lines, is 2 mm $\times$ 2 mm. A side view of the integrated device is shown in Figure 5-4.

![Figure 5-2: Schematic of the integrated transistor amplifier and array read-out circuitry for a $2 \times 2$ array.](image)
Figure 5-3: Layout of one cell of the integrated transistor amplifier and array read-out circuit. The cell is 10 mm $\times$ 10 mm. The diaphragm, indicated by the red square boundary lines, is 2 mm $\times$ 2 mm. $+$ and $-$ are the plus and minus terminals as shown in the schematic in Figure 5-2, $G$ is the ground terminal, $C$ is the column select line and $R$ is the row output line. The two different shades of blue represent two different planes of conducting metal. The gate oxides of the three MOSFETS (green) are partially covered by aluminum contacts (black squares) and polysilicon gates (very narrow violet rectangles).
Figure 5-4: Side view of the strain-gauge pressure sensor with integrated transistor amplifier and array read-out circuitry.
In the first generation of this device, the wafer would have a 5 \times 5 array of sensors, each occupying a 10 mm \times 10 mm cell. This gives each cell plenty of real estate on the wafer to reduce conduction line resistance and build physically large transistors to ensure their reliability. Like with the Round 4 devices, all the diaphragms on a wafer would share a common air cavity via a snaking air channel etched in the Pyrex wafer.

The process flow for the integrated pressure sensor is longer than the devices fabricated for this thesis, but is not much more complex. It combines standard transistor fabrication with the fabrication process described in Section 3.1 with no additional steps. First, the Pyrex wafer are prepared as before. Next, silicon nitride is deposited on the SOI wafer and most of the front-side is removed while a protective nitride ring (Subsection 3.4.3) is retained. This is followed by a standard four-mask transistor fabrication routine:

- Field oxidation for transistors;
- Pattern active area;
- Gate oxidation for transistors;
- Create polysilicon gate;
- Reoxidation/activation;
- Pattern contact holes;
- Add aluminum contacts.

The remainder of the strain-gauge pressure sensor fabrication then takes place:

- KOH etch to release diaphragms;
- Bond Pyrex and SOI wafers;
- Create resistors;
- Add Parylene.
However, once the aluminum is deposited, piranha cannot be used. Thus, any cleaning or photoresist stripping steps afterwards involving piranha are replaced by Nano-Strip\textsuperscript{TM}. Placing transistor fabrication early in the process flow allows for the testing of dummy transistors before the comparatively more straightforward but time-consuming KOH etching step (which can only be done one wafer at a time, with each etch taking around 8 hours).

Appendix Section C.4 shows the complete fabrication process flow for the integrated sensors.

5.3.4 Flexible substrates

As discussed in Chapter 1, while this thesis built a silicon-based sensor system, a device fabricated from flexible materials would be beneficial for AUVs, which have curved surfaces and be more robust in the mechanically rough undersea environment. Furthermore, the abandonment of KOH-etching silicon removes the restriction that the diaphragms be rectangular. This would allow for more novel shapes and locations for pressure sensors in the array.

Members of our research group recently presented progress towards creating an artificial lateral line using an entirely elastomer material set to provide flexibility and waterproofing. Typically, elastomer-based pressure sensors are limited by large hysteresis and low sensitivity, so they have been used mainly for tactile applications. [96] addresses this limitation by adopting a MEMS-based sensor geometry. Each sensor consists of a polydimethysiloxane (PDMS) diaphragm and a resistive strain gauge made of a conductive carbon black-PDMS composite. A functional linear array of four sensors with a 15 mm center-to-center spacing has been demonstrated to be capable of underwater operation with 1.5 Pa resolution. However, it still suffers from hysteresis and has a repeatability of about 22% of the input pressure signal amplitude, due to creep. A diagram and photograph of the elastomer-based pressure sensors are shown in Figure 5-5.

The integrated amplifier and array read-out circuitry described earlier can also be implemented in flexible polymer materials using organic transistors or other novel components that do not require silicon. For example, other members of our group have recently
demonstrated the design and fabrication of a MEMS switch that employs a metal-polymer nanocomposite as its active material [64]. The nanocomposite is formed by doping a polymer with conducting nanoparticles. The conductivity of the nanocomposite changes 10,000-fold as it is mechanically compressed. Since squeezing initiates the switching behavior, the device is referred to as a “squitch” (Figure 5-6). Other researchers have developed conformable large-area networks of pressure sensors based on an organic semiconductor to create an electronic artificial skin (E-skin) [75, 74]. Flexible, capacitive pressure sensors have also been fabricated over large areas by integrating PDMS films with organic field-effect transistors [57]. Finally, three-axis capacitive tactile sensors have been used to measure the deformation of PDMS membranes by the contact force applied to each cell [50]. Combinations of these devices could be adapted for use as polymer-based underwater pressure sensors.
Figure 5-6: Diagram of the three-terminal squitch described in [64].
Appendix A

Chemical Formulas

The chemical formulas for the common names and abbreviations of chemicals used in Appendices B and C are given in Table A.1.

Table A.1: Chemical formulas and full names.

<table>
<thead>
<tr>
<th>Term</th>
<th>Chemical Formula / Full Name</th>
<th>Target Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>50:1 HF</td>
<td>50 H$_2$O : 1 49% hydrofluoric acid (HF)</td>
<td>Etches SiO$_2$</td>
</tr>
<tr>
<td>Acetone</td>
<td>(CH$_3$)$_2$ CO</td>
<td>Cleaning; strips PR</td>
</tr>
<tr>
<td>Aqua regia$^1$</td>
<td>3 hydrochloric acid (HCl) : 1 nitric acid (HNO$_3$)</td>
<td>Etches gold</td>
</tr>
<tr>
<td>BOE</td>
<td>Buffered oxide etch; 5 40% ammonium fluoride (NH$_4$F) : 1 49% hydrofluoric acid (HF)</td>
<td>Etches SiO$_2$</td>
</tr>
<tr>
<td>Cr-7</td>
<td>Chromium etchant; 9% (NH$_4$)$_2$Ce(NO$_3$)$_6$ + 6% HClO$_4$ + H$_2$O</td>
<td>Etches chromium</td>
</tr>
<tr>
<td>Gold etchant TFA</td>
<td>Gold etchant thin film type A; 30% potassium iodide (KI), 1.3% iodine (I$_2$), 68.7% water (H$_2$O)</td>
<td>Etches gold</td>
</tr>
<tr>
<td>HMDS</td>
<td>Hexamethyldisilazane; NH$_2$Si(CH$_3$)$_3$</td>
<td>Adhesion for PR</td>
</tr>
<tr>
<td>Isopropanol; IPA</td>
<td>(CH$_3$)$_2$ CHOH</td>
<td>Cleaning</td>
</tr>
<tr>
<td>Methanol</td>
<td>CH$_3$OH</td>
<td>Cleaning</td>
</tr>
<tr>
<td>Piranha</td>
<td>3 sulfuric acid (H$_2$SO$_4$) : 1 hydrogen peroxide (H$_2$O$_2$)</td>
<td>Cleaning; strips PR</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>H$_3$PO$_4$</td>
<td>Etches Si$_3$N$_4$</td>
</tr>
<tr>
<td>PR</td>
<td>Photoresist. AZ 917 was used for mask-making; OCG 934 for everything else.</td>
<td>Photolithographic masking material</td>
</tr>
</tbody>
</table>

$^1$Latin for “royal water”. It should not be confused with acquaragia, which is commonly known as turpentine in English.
Appendix B

Standard Operating Procedures

This appendix contains key standard operating procedures (SOPs) used for the process flows in Appendix C. The relevant section of the main text that discusses each procedure is indicated in parentheses.

- B.1: Mask-making (Section 3.3);
- B.2: TRL photolithography (Section 3.3);
- B.3: KOH etching (Section 3.4);
- B.4: Post-KOH clean (Section 3.4);
- B.5: Hot phosphoric (Section 3.6);
- B.6: EV501 and anodic bonding (Section 3.6).

The chemical formulas for the common names and abbreviations used are given in Appendix A. All processing was done at the MIT Microsystems Technology Laboratories (MTL), which consists of three facilities: Technology Research Laboratory (TRL), Integrated Circuits Laboratory (ICL) and Exploratory Materials Laboratory (EML).
B.1 Mask-Making

Approximate Time: 60 minutes

1. Cut out the transparency mask so that it is 7" by 7".

2. Clean the glass plate near EV1 with acetone, methanol and isopropanol, in that order.

3. Create a stack in the following manner: Put the blank glass-chromium mask on the bottom with the chromium and PR side up. Put the transparency in the middle with the ink side down. Finally, put the glass plate on top. The pattern is effectively upside-down compared to the usual mask usage.

4. Expose the stack on EV1 with flood exposure for 5.0 seconds.

5. Put the blank mask into a mask carrier.

6. Pour AZ 917 developer into a blue container.

7. Develop the blank mask in AZ 917 for 90 seconds. Let the mask sit in the developer for 30 seconds before agitating.

8. Dump rinse and blow dry the mask.

9. In an acidhood, rinse out and blow dry the blue container. It is important that the container is dry.

10. Pour Cr-7 into the blue container. Etch the exposed chromium on the mask for 90 seconds.

11. Aspirate and clean the blue container.

12. Pour nanostrip into the blue container. Strip PR from the mask for 5 minutes.

13. Aspirate and clean the blue container.

14. Dump rinse and blow dry the mask.
B.2. TRL PHOTOGRAPHY

B.2 TRL Photolithography

Approximate Time: At least 2 hours

1. HMDS
   (a) Load wafers into the metal boat. Be sure to use the correct (Au vs. non-Au) ones. **Important:** Do not put wafers that have PR on them in the HMDS machine.
   (b) Put the boat into the HMDS machine using the appropriate grip.
   (c) Select recipe 5 and press “start”.
   (d) After 20–25 minutes, the machine will emit a sound.
   (e) Press reset and place boat in the glass dish to cool.

2. Coater
   (a) Replace the coater wafer holder with a 6” one. Clean it with acetone and blow dry.
   (b) Set the photoresist setting to 1.
   (c) Hold the round wafer carrier in your left hand. Use your right hand to place the wafer on the round wafer carrier.
   (d) Place the wafer on the wafer holder. Be sure that it is centered.
   (e) Turn on the vacuum (when the vacuum light is **on**, the vacuum is **off**) and carefully remove the wafer carrier without touching the wafer.
   (f) Set the rightmost time settings to 9.0 s, 6 s and 30 s.
   (g) Move the dispenser to the side and test run by pressing “start” to let the old PR drip. Set the three speeds to 500 RPM, 750 RPM and 3000 RPM during the test run. Make sure that the wafer is centered; if not, fix it.
   (h) Move the dispenser over the wafer.
   (i) Press “start”.
   (j) While the dispenser is releasing PR, move it back and forth over the wafer.
   (k) When the dispenser stops releasing PR and the wafer spins faster, move the dispenser to the side so that any further drips will not ruin the PR coat.
   (l) When the wafer stops spinning, release the vacuum and use the round wafer carrier to move the wafer into the regular wafer boat.
   (m) Repeat these steps for each wafer.

3. Pre-Bake
   (a) Put the wafers in the 90°C pre-bake oven for 30 minutes.
   (b) Allow the wafers to cool.
APPENDIX B. STANDARD OPERATING PROCEDURES

(c) **Important:** If you are not exposing the wafers immediately, be sure to store the wafers in a UV-free environment.

4. EV1

(a) Open the program using “g” as both the username and password.

(b) Select the appropriate recipe. Use the parameters “continuous,” “soft contact” and “2.3 s” exposure time. Most masks are 2.3 mm thick. Be sure to enter the correct wafer thickness (standard is 650 μm).

(c) Change the mask holder and wafer chuck for the appropriate size and color designation.

(d) Set the $x$, $y$ and $\theta$ coordinates to (5, 5, 5).

(e) Henceforth, follow the instructions on the screen.

(f) Place the mask frame on the wafer chuck.

(g) Load the mask chromium side **down**.

(h) After the mask is in the machine, use the optics to locate key features. Store their coordinates.

(i) Remove the mask frame.

(j) Load the wafer on the wafer chuck.

(k) After the wafer is in the machine, use the optics to align features to the mask.

(l) Expose the wafer.

(m) Repeat for each wafer.

(n) When finished, exit, park, and log out.

5. Develop

(a) Fill a green round plastic container with OCG 934 1:1 developer.

(b) Put a wafer in the developer for 60 s. Gently move the container in circles and use a wafer holder to move the wafer up and down. Be sure that the features are visible.

(c) Rinse the wafer over the faucet.

(d) Dump the developer.

(e) Repeat above steps for each wafer.

(f) When all wafers are developed, dump rinse them together.

(g) Spin dry the wafers.

6. Post-Bake

(a) Put the wafers in the 120°C post-bake oven for 30 minutes.

(b) Allow the wafers to cool.
B.2.1 Double-sided PR

When both sides of a wafer are to be coated, but only one side is to be exposed, do the following procedure.

1. HMDS
2. Spincoat PR on the side that \textit{won't} be exposed.
3. Prebake for 15 minutes.
4. Let the wafer cool.
5. Spincoat PR on the side that \textit{will} be exposed.
6. Prebake for 30 minutes.
7. Expose to EV1.
8. Develop.
9. Post-bake for 30 minutes.

B.2.2 With paint

Spincoating PR does not cover the edge of the wafer. When complete coverage is necessary, additional PR is painted onto the edge before prebaking.
B.3 KOH Etching

Approximate Time: Varies

1. Put the wafers in a dedicated KOH transfer wafer box and bring them to EML, where the ICL TMAH-KOH station is located.

2. Gown up.

3. Turn on the hot bath and make sure the target temperature is set to 85°C.

4. Fill the bath up with water with the spray gun so that the floating balls no longer touch the bars on the walls of the bath.

5. Take the glass square beaker out of the KOH cabinet below the station. Rinse it out.

6. Use the graduated cylinder from the same cabinet to put 3 L of water into the square beaker. Put the beaker in the bath. Make sure that the height of the bath water exceeds that in the square beaker.

7. From the KOH cabinet to the right of the station, take out a plastic beaker. Put it on the electronic scale and zero it.

8. Take out bottles of KOH pellets from the lower cabinet to the right of the station. Pour KOH pellets into the plastic beaker until the scale reads 750 g.

9. Pour the KOH pellets into the square beaker. Use a wand to stir the mixture until all of the KOH is dissolved.

10. Put the square lid over the square beaker so that water does not evaporate away. Put the clear lid over the entire bath.

11. Put away the measuring equipment and wait until the bath temperature has reached 80°C. This takes about one hour.

12. Remove both layers of lids.

13. Put the wafers into a teflon wafer carrier.

14. Prepare a 50:1 HF solution using the 49% HF bottle from the acid room. Be sure the solution is in a teflon container.

15. Place the wafers into the HF solution for 30 seconds to etch away any native oxide.

16. Place the wafers directly into the bath horizontally. If possible, place the wafers into the middle slots.

17. Important: Put the lids back on the square beaker and the bath. Otherwise, water will evaporate and the KOH concentration in the beaker will change over time.
18. A 20% KOH mixture at 80°C etches at 80 μm/min. Wait for the appropriate length of time.

19. When the etch is finished, take off the lids. Take the wafer carrier out of beaker and place it in the cascade rinse. Turn on the rinse.

20. Drain the bath.

21. Pour out the square beaker containing the KOH solution. Rinse it thoroughly and put it back in the lower cabinet.

22. When the wafers have been thoroughly rinsed, turn off the cascade rinse and blow dry the wafers.

23. Examine the etch under the microscope.

24. Put the wafers back into the KOH transfer box. They are now ready for post-KOH clean.

25. Clean up the lab station.
B.4 Post-KOH Clean

Approximate Time: 90 minutes

1. Open the post-KOH clean box of wafers near Acidhood 1 before suiting up. Acidhood 2 may not be used.

2. Suit up.

3. Get a yellow wafer boat (with gloves) and transfer wafers to the boat (without gloves).

4. Get a yellow plastic vat (for water only), a yellow glass vat, and a green glass vat. The glass vats will contain piranha, which is a 3:1 solution of sulfuric acid ($H_2SO_4$) and hydrogen peroxide ($H_2O_2$); the ratio does not have to be exact. Remember: Add acid.

5. Fill the yellow plastic vat with water from the sink.

6. Use a top-type yellow wafer handler to put the wafers in the yellow plastic vat.

7. Go to the acid storage and get a bottle of hydrogen peroxide and at least two full bottles of sulfuric acid. Bring them to the acid hood.

8. Pour hydrogen peroxide into both glass vats so that the depth is 4–6 cm.

9. Add about three times the amount of sulfuric acid into both glass vats. The solutions should be warm and vapors should be forming.

10. Take the boat out of the yellow plastic vat and transfer it directly into the yellow glass vat. Begin 10-minute countdown.

11. Rinse the yellow plastic vat and return it to the shelf.

12. When the 10 minutes are up, place the boat in the dump rinser and set for 5 rinses.

13. Aspirate and clean the yellow glass vat.

14. Transfer the wafers from the yellow boat to a green boat.

15. Put the wafers into the green glass vat and begin the 10-minute countdown.


17. When the 10 minutes are up, place the boat in the dump rinser and set for 5 rinses (second time).

18. Aspirate and clean the green glass vat.

19. Put the wafers into the HF solution for 30 seconds.

20. Place the boat in the dump rinser and set for 5 rinses (third time).
21. Aspirate and clean the green plastic vat.

22. Spin dry the wafers.

23. Clean up the acid station.
B.5  Hot Phosphoric

Approximate Time: 2–4 hours

B.5.1  ICL hot phosphoric

If the wafer is allowed in ICL (e.g., it is not in pieces), then use the dedicated hot phosphoric station in ICL to remove nitride.

1. Suit up.

2. Check whether the acid goes up to the gray line. If not, ask Paul Tierney for help.

3. Press “on” and “reset” to heat up the bath to 165°C. This takes about one hour.

4. Put the wafers in the dedicated wafer boat.

5. Hold the wafer boat above the acid for one minute to allow it to heat up slowly in the vapors.

6. Slowly place the boat in the acid bath. Be sure that the wafer holder is oriented forward-back, not left-right.

7. Phosphoric acid (H₃PO₄) at 160°C etches nitride at 50 Å/min; let the wafers sit in the bath for the appropriate period of time.

8. When the wafers are done, slowly take the boat out of the bath and hold the wafers above the acid for one minute.

9. Place the boat on the counter for several minutes to allow the wafers to cool.

10. Run the dump rinse several times without the wafers.

11. Place the wafers in the dump rinse.

12. Do not spin dry the wafers because they might be fragile from KOH etching. Instead, blow dry them.

B.5.2  TRL acid hood

If the wafer is not allowed in ICL (e.g., it is in pieces), then use the TRL acid hood to remove nitride.

1. Fill a glass beaker with phosphoric acid.

2. Put the large hot plate in the acid hood. Put the beaker on it, plug in the hot plate, and turn it on.
3. Place a thermometer in the beaker to monitor the temperature. Be sure that the thermometer’s range is well above 160°C. Wait for the temperature to reach 160°C, which will take about 2 hours.

4. Put the wafers in a boat.

5. Hold the wafer boat above the acid for one minute to allow it to heat up in slowly in the vapors.

6. Slowly place the boat in the acid bath.

7. Phosphoric acid at 160°C etches nitride at 50 Å/min; let the wafers sit in the bath for the appropriate period of time.

8. When the wafers are done, slowly take the boat out of the bath and hold the wafers above the acid for one minute.

9. Place the boat on the counter for several minutes to allow the wafers to cool.

10. Run the dump rinse several times without the wafers.

11. Place the wafers in the dump rinse.

12. Aspirate the phosphoric acid.

13. Clean up the acid hood.
B.6 EV501 and Anodic Bonding

Approximate Time: Varies

1. Clean the SOI wafer and Pyrex wafer to be bonded in piranha for 10 minutes.
2. Clean all tooling with isopropanol (IPA) and fabwipes prior to using.
3. Put on a new pair of vinyl gloves immediately prior to the bonding sequence, after the cleaning step.
4. Transport the wafers from the cleaning station in the teflon boat in which the wafers were cleaned. Do NOT use metal tweezers.
5. Start by making sure the aligner \( x \) and \( y \) verniers are at the 5 \( \mu \)m mark, and adjust the \( \theta \) vernier correctly over the white square.
6. The SOI wafer is loaded first with the bonding surface and alignment marks facing DOWN.
7. The SOI wafer is then aligned via movable bottom mounted CCD cameras in the \( x \) direction, and via verniers in the \( \theta \) and \( y \) directions.
8. The SOI wafer is brought into vacuum contact with the bondchuck, and electronically generated crosshairs are then positioned over the still visible crosshairs.
9. Insert wafer separation spacers called FLAGS, and then load the Pyrex wafer with bond surface facing UP, to mate with the SOI wafer. Note: the second wafer must have alignment marks on the non-bonding surface, in addition to any which may be on the bonding surface.
10. The Pyrex wafer is moved, with verniers, to align with the electronic crosshair registers, and the bond occurs with SDB, or the bondchuck clamps the loadframe / wafer / flag / wafer stack in place, for bonding.
11. Use software program AB1 on the "menu", and the Au-compatible bondchuck, loadframe, and the GRAPHITE pressure diffuser, which will act as a cathode in this process.
12. When installing the bondchuck, make absolutely sure the clamps are in their recesses. If not, they will break the $1500 quartz loadframe when contact is made.
13. Set thickness of the bonder to the combined wafer thickness plus 3 mm.
14. Place the stack in the bonder and lock it. The Pyrex is on top; the electrode puck is in contact with the Pyrex.
15. Turn on the bonder.
16. Start the recipe (see below).

17. When the process has terminated, wait for the bonder temperature to reach near room temperature.

18. Unlock the bonder and remove the bonded wafers.

19. Lock the bonder to keep it clean.

Table B.1: Recipe for bonding silicon and Pyrex.

<table>
<thead>
<tr>
<th>Step</th>
<th>Command</th>
<th>Param 1</th>
<th>Param 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Waferbow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Wait</td>
<td>Time</td>
<td>0:00:20</td>
</tr>
<tr>
<td>3</td>
<td>Heating</td>
<td>350</td>
<td>0:00:00</td>
</tr>
<tr>
<td>4</td>
<td>Set temp. top</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Wait</td>
<td>Temp. bottom</td>
<td>350</td>
</tr>
<tr>
<td>6</td>
<td>Wait</td>
<td>Temp. top</td>
<td>350</td>
</tr>
<tr>
<td>7</td>
<td>Wait</td>
<td>Time</td>
<td>0:00:10</td>
</tr>
<tr>
<td>8</td>
<td>Flags out</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Wait</td>
<td>Time</td>
<td>0:00:10</td>
</tr>
<tr>
<td>10</td>
<td>Piston down</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Voltage on</td>
<td>Intern neg.</td>
<td>1000</td>
</tr>
<tr>
<td>12</td>
<td>Wait</td>
<td>Time</td>
<td>0:05:00</td>
</tr>
<tr>
<td>13</td>
<td>Wait</td>
<td>Current &lt;</td>
<td>5</td>
</tr>
<tr>
<td>14</td>
<td>Wait</td>
<td>Time</td>
<td>0:05:00</td>
</tr>
<tr>
<td>15</td>
<td>Voltage off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Piston up</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Cooling</td>
<td>155</td>
<td>0:00:00</td>
</tr>
<tr>
<td>18</td>
<td>Wait</td>
<td>Temp. top</td>
<td>200</td>
</tr>
<tr>
<td>19</td>
<td>Vent on</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Wait</td>
<td>Time</td>
<td>0:01:00</td>
</tr>
<tr>
<td>21</td>
<td>Purge off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>** END **</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix C

Process Flows

This appendix contains the process flows and recipes used. The photolithography process flow was described beginning on Page 92 in Section 3.3. The remarks regarding the procedure for finding the crystalline plane for (100) silicon can be found beginning on Page 117 in Section 3.8. The Pyrex process flow shown as part of the device process flows is identical to the one shown in Table 3.3 on Page 104. Diagrams and explanations of the device process flows can be found beginning on Page 86 in Section 3.1. Discussion about the strain-gauge silicon sensors with transistors can be found beginning on Page 170 in Section 5.3.

The chemical formulas for the common names and abbreviations used are given in Appendix A. Key standard operating procedures (SOPs) used for the process flows are given in Appendix B. All processing was done at the MIT Microsystems Technology Laboratories (MTL), which consists of three facilities: Technology Research Laboratory (TRL), Integrated Circuits Laboratory (ICL) and Exploratory Materials Laboratory (EML).
C.1 Standard Photolithography

Tables C.1 and C.2 show the process flow for all single- and double-sided photolithography procedures, respectively. For the double-sided photolithography, only one side is etched.

Table C.1: Process flow for standard single-sided photolithography.

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.1</td>
<td>HMDS</td>
<td>TRL</td>
<td>HMDS</td>
<td>Recipe 5</td>
</tr>
<tr>
<td>S.2</td>
<td>Coat PR</td>
<td>TRL</td>
<td>Coater</td>
<td>PR 1; 500 RPM (9.0 s), 750 RPM (6 s), 3000 RPM (30 s)</td>
</tr>
<tr>
<td>S.3</td>
<td>Pre-bake</td>
<td>TRL</td>
<td>Pre-bake</td>
<td>30 min</td>
</tr>
<tr>
<td>S.4</td>
<td>Expose</td>
<td>TRL</td>
<td>EV1</td>
<td>2.3 s</td>
</tr>
<tr>
<td>S.5</td>
<td>Develop</td>
<td>TRL</td>
<td>Develop hood</td>
<td>OCG 934 1:1, 60 s</td>
</tr>
<tr>
<td>S.6</td>
<td>Post-bake</td>
<td>TRL</td>
<td>Post-bake</td>
<td>30 min</td>
</tr>
</tbody>
</table>

Table C.2: Process flow for standard double-sided photolithography.

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.1</td>
<td>HMDS</td>
<td>TRL</td>
<td>HMDS</td>
<td>Recipe 5</td>
</tr>
<tr>
<td>D.2</td>
<td>Coat PR</td>
<td>TRL</td>
<td>Coater</td>
<td>PR 1; 500 RPM (9.0 s), 750 RPM (6 s), 3000 RPM (30 s)</td>
</tr>
<tr>
<td>D.3</td>
<td>Pre-bake</td>
<td>TRL</td>
<td>Pre-bake</td>
<td>15 min</td>
</tr>
<tr>
<td>D.4</td>
<td>Coat PR</td>
<td>TRL</td>
<td>Coater</td>
<td>PR 1; 500 RPM (9.0 s), 750 RPM (6 s), 3000 RPM (30 s)</td>
</tr>
<tr>
<td>D.5</td>
<td>Pre-bake</td>
<td>TRL</td>
<td>Pre-bake</td>
<td>30 min</td>
</tr>
<tr>
<td>D.6</td>
<td>Expose</td>
<td>TRL</td>
<td>EV1</td>
<td>2.3 s</td>
</tr>
<tr>
<td>D.7</td>
<td>Develop</td>
<td>TRL</td>
<td>Develop hood</td>
<td>OCG 934 1:1, 60 s</td>
</tr>
<tr>
<td>D.8</td>
<td>Post-bake</td>
<td>TRL</td>
<td>Post-bake</td>
<td>30 min</td>
</tr>
</tbody>
</table>
C.2 Finding the Crystalline Plane for (100) Silicon

Starting material:

- 150 mm wafers with (100) silicon on at least one side (target side)

Table C.3: Process flow for finding the crystalline plane for (100) silicon.

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean wafers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Clean</td>
<td>ICL</td>
<td>RCA hood</td>
<td>Standard</td>
</tr>
<tr>
<td>Set up nitride mask</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Nitride</td>
<td>ICL</td>
<td>VTR nitride</td>
<td>775°C, 200 mTorr, SiCl₂H₂ at 50 sccm and NH₃ at 150 sccm, 23 ang/min OR VTR</td>
</tr>
<tr>
<td>Etch (110) rectangles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Photo (target)</td>
<td>TRL</td>
<td>Coater/EV1</td>
<td>Standard w/ paint</td>
</tr>
<tr>
<td>4</td>
<td>Etch</td>
<td>ICL</td>
<td>LAM490B</td>
<td>Nitride-on-Si</td>
</tr>
<tr>
<td>5</td>
<td>Ash</td>
<td>TRL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>6</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>7</td>
<td>KOH Etch</td>
<td>ICL</td>
<td>TMAH-KOH</td>
<td>20%, 80°C</td>
</tr>
<tr>
<td>8</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>9</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>1:4 HCl:H₂O, 5 min</td>
</tr>
<tr>
<td>Find crystalline plane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Observe</td>
<td>TRL</td>
<td>Microscope</td>
<td>Standard</td>
</tr>
</tbody>
</table>
C.3 Strain-Gauge Silicon Sensors Without Transistors

The following charts show the process flow for Round 4 devices. The manner in which the process flows for Rounds 1, 2, 3a and 3b differ from that of Round 4 is explained at the end of Section 3.1.

Starting materials:

- 150 mm SOI wafers: Double-side polished (100) silicon with 20 µm n-type epi-layer
- 150 mm Pyrex wafers: Corning Pyrex 7740

The process flow is arranged into the following tables:

- Table C.4 describes the preparation of Pyrex for bonding with SOI.
- Tables C.5 and C.6 describe partial sensor fabrication on SOI wafers. They are independent of Table C.4.
- Table C.7 describes bonding of SOI with Pyrex and the remainder of the sensor fabrication.
### C.3. STRAIN-GAUGE SILICON SENSORS WITHOUT TRANSISTORS

Table C.4: Process flow for Pyrex wafers for strain-gauge silicon sensors without transistors.

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>2</td>
<td>Clean</td>
<td>TRL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>3</td>
<td>Metal</td>
<td>TRL</td>
<td>E-beam</td>
<td>Standard</td>
</tr>
<tr>
<td>4</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>5</td>
<td>Clean</td>
<td>TRL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>6</td>
<td>Metal</td>
<td>TRL</td>
<td>E-beam</td>
<td>Standard</td>
</tr>
<tr>
<td>7</td>
<td>Photo (front)</td>
<td>TRL</td>
<td>Coater/EV1</td>
<td>Standard (double-sided)</td>
</tr>
<tr>
<td>8</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>28 Å/s</td>
</tr>
<tr>
<td>9</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>25 Å/s</td>
</tr>
<tr>
<td>10</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>0.8 μm/min</td>
</tr>
<tr>
<td>11</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>12</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>25 Å/s</td>
</tr>
<tr>
<td>13</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>28 Å/s</td>
</tr>
<tr>
<td>14</td>
<td>Storage</td>
<td>TRL</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table C.5: Process flow for SOI wafers for strain-gauge silicon sensors without transistors.

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean wafers</td>
<td>Clean</td>
<td>ICL</td>
<td>RCA hood</td>
<td>Standard</td>
</tr>
<tr>
<td>Set up protective nitride layer and ring</td>
<td>Nitride</td>
<td>ICL</td>
<td>VTR nitride</td>
<td>775°C, 200 mTorr, SiCl2H2 at 50 sccm and NH3 at 150 sccm, 23 Angstrom/min OR VTR</td>
</tr>
<tr>
<td>16</td>
<td>Photo (front)</td>
<td>TRL</td>
<td>Coater/EV1</td>
<td>Standard w/ paint</td>
</tr>
<tr>
<td>17</td>
<td>Etch</td>
<td>ICL</td>
<td>LAM490B OR AME5000</td>
<td>Nitride-on-Si OR Standard</td>
</tr>
<tr>
<td>18</td>
<td>Ash</td>
<td>TRL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>19</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
</tbody>
</table>
Table C.6: Process flow for SOI wafers for strain-gauge silicon sensors without transistors (cont.).

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Create oxide insulation</td>
<td>21</td>
<td>Clean</td>
<td>ICL</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>Oxide Growth</td>
<td>OR</td>
<td>ICL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Set up creation of diaphragm</td>
<td>23</td>
<td>Photo (back)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24</td>
<td>Etch</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25</td>
<td>Ash</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26</td>
<td>Strip</td>
</tr>
<tr>
<td></td>
<td>Create alignment marks on front-side oxide for aligning resistors later (not necessary if Mask O has alignment marks)</td>
<td>27</td>
<td>Photo (front)</td>
<td>TRL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28</td>
<td>Etch</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>29</td>
<td>Ash</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>Strip</td>
</tr>
<tr>
<td></td>
<td>Create diaphragm</td>
<td>31</td>
<td>KOH Etch</td>
<td>ICL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>32</td>
<td>Etch</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33</td>
<td>Clean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34</td>
<td>Clean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35</td>
<td>Etch</td>
</tr>
</tbody>
</table>
Table C.7: Remainder of process flow for strain-gauge silicon sensors without transistors.

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bond Pyrex and SOI wafers</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Align</td>
<td>TRL</td>
<td>EV620</td>
<td>Standard</td>
</tr>
<tr>
<td>37</td>
<td>Bond</td>
<td>TRL</td>
<td>EV501</td>
<td>Standard</td>
</tr>
<tr>
<td><strong>Create resistors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>39</td>
<td>Metal</td>
<td>TRL</td>
<td>E-beam</td>
<td>Standard</td>
</tr>
<tr>
<td>40</td>
<td>Photo (front)</td>
<td>TRL</td>
<td>Coater/EV1</td>
<td>Standard</td>
</tr>
<tr>
<td>41</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>42</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>43</td>
<td>Ash</td>
<td>TRL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>44</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td><strong>Add Parylene</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>Deposition</td>
<td>TRL</td>
<td>Parylene</td>
<td>Standard</td>
</tr>
<tr>
<td><strong>Test devices</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>Test</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
C.4 Strain-Gauge Silicon Sensors With Transistors

Starting materials:

- 150 mm SOI wafers: Double-side polished (100) silicon with 20 µm n-type epi-layer
- 150 mm Pyrex wafers: Corning Pyrex 7740

The process flow is arranged into the following tables:

- Table C.8 describes the preparation of Pyrex for bonding with SOI.
- The sequence of Tables C.9, C.10 and C.11 describe transistor fabrication and partial sensor fabrication on SOI wafers. They are independent of Table C.8.
- Table C.12 describes bonding of SOI with Pyrex and the remainder of the sensor fabrication.
Table C.8: Process flow for Pyrex wafers for strain-gauge silicon sensors with transistors.

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>2</td>
<td>Clean</td>
<td>TRL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>3</td>
<td>Metal</td>
<td>TRL</td>
<td>E-beam</td>
<td>Standard</td>
</tr>
<tr>
<td>4</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>5</td>
<td>Clean</td>
<td>TRL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>6</td>
<td>Metal</td>
<td>TRL</td>
<td>E-beam</td>
<td>Standard</td>
</tr>
<tr>
<td>7</td>
<td>Photo (front)</td>
<td>TRL</td>
<td>Coater/EV1</td>
<td>Standard (double-sided)</td>
</tr>
<tr>
<td>8</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>28 Å/s</td>
</tr>
<tr>
<td>9</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>25 Å/s</td>
</tr>
<tr>
<td>10</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>0.8 μm/min</td>
</tr>
<tr>
<td>11</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>12</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>25 Å/s</td>
</tr>
<tr>
<td>13</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>28 Å/s</td>
</tr>
<tr>
<td>14</td>
<td>Storage</td>
<td>TRL</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Table C.9: Process flow for SOI wafers for strain-gauge silicon sensors with transistors.

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean wafers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Clean</td>
<td>ICL</td>
<td>RCA hood</td>
<td>Standard</td>
</tr>
<tr>
<td>Set up protective nitride layer and ring</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Nitride</td>
<td>ICL</td>
<td>VTR nitride</td>
<td>775°C, 200 mTorr, SiCl₂H₂ at 50 sccm and NH₃ at 150 sccm, 23 Å/min OR VTR</td>
</tr>
<tr>
<td>17</td>
<td>Photo (front)</td>
<td>TRL</td>
<td>Coater/EV1</td>
<td>Standard w/ paint</td>
</tr>
<tr>
<td>18</td>
<td>Etch</td>
<td>ICL</td>
<td>LAM490B OR AME5000</td>
<td>Nitride-on-Si OR Standard</td>
</tr>
<tr>
<td>19</td>
<td>Ash (optional)</td>
<td>ICL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>20</td>
<td>Strip</td>
<td>ICL</td>
<td>Wet strip</td>
<td>Standard</td>
</tr>
<tr>
<td>Field oxidation for transistors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Clean</td>
<td>ICL</td>
<td>RCA hood</td>
<td>Standard</td>
</tr>
<tr>
<td>22</td>
<td>Oxide Growth</td>
<td>ICL</td>
<td>Tube 5C</td>
<td>Standard</td>
</tr>
<tr>
<td>Pattern active area</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Photo (front)</td>
<td>TRL</td>
<td>Coater/EV1</td>
<td>Standard w/ paint</td>
</tr>
<tr>
<td>24</td>
<td>Etch</td>
<td>ICL</td>
<td>Oxide wet etch</td>
<td>BOE</td>
</tr>
<tr>
<td>25</td>
<td>Ash (optional)</td>
<td>ICL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>26</td>
<td>Strip</td>
<td>ICL</td>
<td>Wet strip</td>
<td>Standard</td>
</tr>
<tr>
<td>Gate oxidation for transistors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Clean</td>
<td>ICL</td>
<td>RCA hood</td>
<td>Standard</td>
</tr>
<tr>
<td>28</td>
<td>Oxide Growth</td>
<td>ICL</td>
<td>Tube 5C</td>
<td>Standard</td>
</tr>
<tr>
<td>Create polysilicon gate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Clean (optional if polySi deposition immediately follows gate oxidation)</td>
<td>ICL</td>
<td>RCA hood</td>
<td>Standard</td>
</tr>
<tr>
<td>30</td>
<td>Deposition</td>
<td>ICL</td>
<td>Tube 6A</td>
<td>Standard</td>
</tr>
<tr>
<td>31</td>
<td>Photo (front)</td>
<td>TRL</td>
<td>Coater/EV1</td>
<td>Standard w/ paint</td>
</tr>
<tr>
<td>32</td>
<td>Etch</td>
<td>ICL</td>
<td>LAM490B OR AME5000</td>
<td>Cl₂ OR CF₄</td>
</tr>
<tr>
<td>33</td>
<td>Ash</td>
<td>ICL</td>
<td>Asher</td>
<td>Standard</td>
</tr>
<tr>
<td>34</td>
<td>Strip</td>
<td>ICL</td>
<td>Wet strip</td>
<td>Standard</td>
</tr>
<tr>
<td>Ion implantation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Implantation</td>
<td>Off-campus</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
### C.4. STRAIN-GAUGE SILICON SENSORS WITH TRANSISTORS

Table C.10: Process flow for SOI wafers for strain-gauge silicon sensors with transistors (cont.).

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>ICL</td>
<td>Piranha / HF</td>
<td>Standard</td>
<td>Double piranha &amp; HF dip</td>
</tr>
<tr>
<td>37</td>
<td>ICL</td>
<td>RCA hood</td>
<td>Standard</td>
<td>RCA clean</td>
</tr>
<tr>
<td>38</td>
<td>ICL</td>
<td>Tube 5B</td>
<td>Standard</td>
<td>Grow 500 Å oxide on front-side (950 °C, dry 15 min, wet 7 min, dry 15 min)</td>
</tr>
</tbody>
</table>

**Pattern contact holes**

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>ICL</td>
<td>Tube 5B</td>
<td>Standard</td>
<td>Add aluminum contacts</td>
</tr>
<tr>
<td>44</td>
<td>ICL</td>
<td>Endura</td>
<td>Standard</td>
<td>Sputter 1 µm Al-1%Si on front</td>
</tr>
<tr>
<td>45</td>
<td>ICL</td>
<td>PAN etch</td>
<td>Standard</td>
<td>Mask NM</td>
</tr>
<tr>
<td>46</td>
<td>ICL</td>
<td>PAN etch</td>
<td>Standard</td>
<td>Etch oxide from back of wafer (metal only on the side not being etched)</td>
</tr>
</tbody>
</table>

Table C.11: Process flow for SOI wafers for strain-gauge silicon sensors with transistors (conc.).

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>ICL</td>
<td>TMAH-KOH</td>
<td>20%, 80°C with HF dip, use red lollipop</td>
<td>Etch silicon from back-side with KOH (front-side protected)</td>
</tr>
<tr>
<td>51</td>
<td>ICL</td>
<td>TMAH-KOH</td>
<td>Timed, use red lollipop</td>
<td>Etch away exposed sandwiched oxide &amp; back-side oxide immediately after KOH (front-side protected)</td>
</tr>
<tr>
<td>52</td>
<td>ICL</td>
<td>TMAH-KOH</td>
<td>1:4 HCl:H₂O, 5 min</td>
<td>Precipitation clean</td>
</tr>
</tbody>
</table>
Table C.12: Remainder of process flow for strain-gauge silicon sensors with transistors.

<table>
<thead>
<tr>
<th>Step</th>
<th>Lab</th>
<th>Machine</th>
<th>Recipe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bond Pyrex and SOI wafers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>59</td>
<td>Align</td>
<td>TRL</td>
<td>EV620</td>
<td>Standard</td>
</tr>
<tr>
<td>60</td>
<td>Bond</td>
<td>TRL</td>
<td>EV501</td>
<td>Standard</td>
</tr>
<tr>
<td>Create resistors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>Clean</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>62</td>
<td>Metal</td>
<td>TRL</td>
<td>E-beam</td>
<td>Standard</td>
</tr>
<tr>
<td>63</td>
<td>Photo (front)</td>
<td>TRL</td>
<td>Coater/EV1</td>
<td>Standard</td>
</tr>
<tr>
<td>64</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>30–60 sec</td>
</tr>
<tr>
<td>65</td>
<td>Strip</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>66</td>
<td>Etch</td>
<td>TRL</td>
<td>Acid hood</td>
<td>Standard</td>
</tr>
<tr>
<td>Add Parylene</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>67</td>
<td>Deposition</td>
<td>TRL</td>
<td>Parylene</td>
<td>Standard</td>
</tr>
<tr>
<td>Test devices</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>68</td>
<td>Test</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Appendix D

Masks

This appendix contains the masks used in all rounds of fabrication. A description of the
design of these masks can be found in Section 3.8. Table D.1 lists the specific model in each
mask category for each round.

<table>
<thead>
<tr>
<th>Round</th>
<th>P</th>
<th>N</th>
<th>O</th>
<th>M</th>
<th>D</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D-1</td>
<td>D-2</td>
<td>—</td>
<td>D-3</td>
<td>D-4</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>D-5</td>
</tr>
<tr>
<td>3a</td>
<td>D-1</td>
<td>D-2</td>
<td>—</td>
<td>D-3</td>
<td>D-6</td>
<td>D-5</td>
</tr>
<tr>
<td>3b</td>
<td>D-7</td>
<td>—</td>
<td>D-8</td>
<td>—</td>
<td>D-9</td>
<td>D-5</td>
</tr>
<tr>
<td>4</td>
<td>D-10</td>
<td>—</td>
<td>D-11</td>
<td>—</td>
<td>D-12</td>
<td>D-13</td>
</tr>
</tbody>
</table>

Table D.1: List of masks used for each round of devices. Each cell contains the figure
number of the mask.
Figure D-1: Mask P (Rounds 1 and 3a).
Figure D-2: Mask N (Rounds 1 and 3a).
Figure D-3: Mask M (Rounds 1 and 3a).
Figure D-4: Mask D (Round 1).
Figure D-5: Mask R (Rounds 2, 3a and 3b).
Figure D-6: Mask D (Round 3a).
Figure D-7: Mask P (Round 3b).
Figure D-8: Mask O (Round 3b).
Figure D-9: Mask D (Round 3b).
Figure D-10: Mask P (Round 4).
Figure D-11: Mask O (Round 4).
Figure D-12: Mask D (Round 4).
Figure D-13: Mask R (Round 4).
Appendix E

Apparatus

This appendix contains technical diagrams of the various apparatus used in fabrication and measurement.
Figure E-1: KOH wafer holder: bottom view of bottom piece.
Figure E-2: KOH wafer holder: bottom view of top piece.
Figure E-3: KOH wafer holder: top view of top piece.
Figure E-4: Tech-Etch cable.
Appendix F

MATLAB

This appendix contains the code for the MATLAB simulation, `resistor_design.m`, used to aid resistor design. The results of the simulation are discussed in Section 2.7.
APPENDIX F. MATLAB

% Displays the strain lines, optimal resistor direction, and sign of resistor change

%% resistor_design.m

% material properties
nuR = 0.21; % Poisson's ratio (chromium resistor)
uS = 0.0064; % Poisson's ratio (silicon diaphragm, <110> directions)
E = 169e9; % Young's modulus [Pa] (silicon diaphragm, <110> directions)
KE = 12*0.00133; % maximum deflection constant (silicon diaphragm, (100) plane)

% diaphragm dimensions
L = 2000e-6; % length [m]
H = 20e-6; % height [m]

% applied pressure
P = 1; % [Pa]

% strain constant (multiply this by normalized strain to get strain)
SC = -KE*(pi^2/2)*(1-nuS^2)*(L/H)^2*(P/E);

% x and y coordinates are normalized to be between -0.5 and +0.5
[x, y] = meshgrid(-0.5:0.005:0.5, -0.5:0.005:0.5);

% normalized strain nsx and nsy are the x- and y-dependent terms of the expression for strain
nsx = (cos(2*pi*x)).*(1 + cos(2*pi*y));
nsy = (cos(2*pi*y)).*(1 + cos(2*pi*x));

% compute the strains in both directions
sx = SC*nsx;
sy = SC*nsy;

close all;

% plot the x-strain; y-strain is inferred by symmetry
figure;
plot3(x, y, sx);
grid on;
xlabel('Normalized x');
ylabel('Normalized y');
zlabel('\epsilon_x/P [Pa^{-1}]');

% compute the local relative change in resistance when the resistor is placed lengthwise in the x and y directions
res_change_x = 1/(1-nuR)*sx + (2*nuR-1)/(1-nuR)*sy;
res_change_y = 1/(1-nuR)*sy + (2*nuR-1)/(1-nuR)*sx;

% show the local optimal lengthwise direction for resistor placement
figure;
for I = 1:size(x,1)
    for J = 1:size(x,2)
        if abs(res_change_x(I,J)) == abs(res_change_y(I,J)) % same
            res_change_opt_dir_color(J,:,I) = [0,0,1]; % blue
        elseif abs(res_change_x(I,J)) > abs(res_change_y(I,J)) % x better
            res_change_opt_dir_color(J,:,I) = [0,1,0]; % green
        else % y better
            res_change_opt_dir_color(J,:,I) = [1,0,0]; % red
        end
    end
    scatter(x(I,:), y(I,:), 4, res_change_opt_dir_color(:,:,I));
    hold on;
end
xlabel('Normalized x');
ylabel('Normalized y');
axis square;
set(gca, 'XTick', [-0.5:0.1:0.5]);
set(gca, 'YTick', [-0.5:0.1:0.5]);

% show the sign of the resistance change when a local resistor
% is placed in the optimal direction
figure;
for I = 1:size(x,1)
    for J = 1:size(x,2)
        if max(abs(res_change_x(I,J)), abs(res_change_y(I,J))) == ...
            max(res_change_x(I,J), res_change_y(I,J)) % the max absolute change is positive
            res_change_opt_dir_sign_color(J,:,I) = [1,0,1]; % magenta
        else % the max absolute is negative
            res_change_opt_dir_sign_color(J,:,I) = [1,1,0]; % yellow
        end
    end
    scatter(x(I,:), y(I,:), 4, res_change_opt_dir_sign_color(:,:,I));
    hold on;
end
xlabel('Normalized x');
ylabel('Normalized y');
axis square;
set(gca, 'XTick', [-0.5:0.1:0.5]);
set(gca, 'YTick', [-0.5:0.1:0.5]);
Bibliography


