MICROMACHINED FLOW SENSORS FOR VELOCITY AND PRESSURE MEASUREMENT

A Dissertation
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Electrical and Computer Engineering

Georgia Institute of Technology
August 2014

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MICROMACHINED FLOW SENSORS FOR VELOCITY AND PRESSURE MEASUREMENT

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To my wife, Jihee Hwang
ACKNOWLEDGEMENTS

It is my great honor to have Dr. Mark G. Allen as my advisor. I enjoyed greatly working in his MSMA group on many interdisciplinary projects including flow and pressure sensors, semiconductor devices, and neuron interfacing devices. He guided me with his wisdom, insightfulness, patience and kindness. I am very grateful to Dr. Allen and proud to be a member of his MSMA group.

After I joined the group, Richard Shafer, the lab manager of the MSMA group, and Avishek Aiyar, a former MSMA group member, helped me to become familiar with the lab tools and laser micromachining. The support from Richard continued through my whole research. I started work in the cleanroom of Georgia Tech from the second year since I joined the MSMA group. Gary Spinner and his team taught me how the cleanroom tools work and how to operate them. I am very grateful to their support and help. I also worked from time to time in Dr. Ari Glezer’s laboratory. I have been working together with his students Daniel Brzozowski and John Kearney during the testing of the flow sensors on airfoils in the wind tunnel. I enjoyed greatly working with them and they shared their knowledge in Fluidics and Aerodynamics, which help me greatly in my flow sensor research. When I was working on the pressure sensor, Minsoo Kim, an MSMA member, helped me dice the pressure references. I am very thankful for his help. During my research, I have also been working with Mandy Luo on a bio-implantable pressure sensor project and Akhil Srinivasan on a regenerative neuron interfacing project. It was a great pleasure to work with both of them. When I prepared for my proposal and defense, Po-Chun “Kirk” Wang, an MSMA member, greatly helped me by sharing his experience.
During my whole Ph.D. period, my wife Jihee Hwang has been with me. Her love helped me overcome difficulties and pass through hard times.
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<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>BSA</td>
<td>Backside Alignment</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal–Oxide–Semiconductor</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Lift Coefficient</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
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<tr>
<td>E-BEAM</td>
<td>Electron Beam</td>
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<tr>
<td>FEM</td>
<td>Finite Element Method</td>
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<tr>
<td>GF</td>
<td>Gauge Factor</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>ICP</td>
<td>Inductive-Coupled Plasma</td>
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<tr>
<td>LPCVD</td>
<td>Low Pressure Chemical Vapor Deposition</td>
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<tr>
<td>MEMS</td>
<td>Microelectromechanical Systems</td>
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<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
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<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma-Enhanced Chemical Vapor Deposition</td>
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<td>PLA</td>
<td>Polylactic Acid</td>
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<td>RIE</td>
<td>Reactive Ion Etching</td>
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<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>TEC</td>
<td>Thermal Expansion Coefficient</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicles</td>
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SUMMARY

This research focuses on developing sensors for properties of aerodynamic interest (i.e., flow and pressure) based on low-cost polymeric materials and simple fabrication processes. Such sensors can be fabricated in large arrays, covering the surface of airfoils typically used in unmanned vehicles, allowing for the detection of flow separation. This in turn potentially enables, through the use of closed-loop control, an expansion of the flight envelope of these vehicles. A key advance is compensation for the typically inferior performance of these low cost materials through both careful design as well as new readout methods that reduce drift, namely a readout methodology based on aeroelastic flutter. Figure 1 shows a schematic outline of the thesis work.

An all-polymer micromachined piezoresistive flow sensor is fabricated, based on a flexible polyimide substrate and an elastomeric piezoresistive composite material. The flow sensor comprises a cantilever that is extended into the embedding flow; flow-induced stress on the cantilever is sensed through the piezoresistive composite material. Increasing the sensitivity of the sensor is achieved by either utilizing a long single-cantilever beam or using a dual-cantilever beam supporting a flap extending into the flow. In the latter case, the sensor demonstrates increased sensitivity with a reduced cantilever length. The increase in sensitivity helps to reduce sensor drift, which in turn is further reduced by a new measurement method, the vibration amplitude measurement method. In this drift reduction measurement method, the flow-induced vibration amplitude of the sensor structure (i.e., the amplitude of the aeroelastic flutter induced by the flow), instead of the absolute value of cantilever deflection, is measured in order to find the flow rate. Measurement of this relative resistance change instead of the absolute
resistance in the piezoresistor rejects common-mode drift and greatly reduces overall drift. Experimental results verify the expected drift reduction. Sensor drift is also reduced when the elastomeric piezoresistive material is replaced by a Pt thin film piezoresistor.

Development of pressure sensors based on polymers proceeds by encapsulating a reference cavity within a multilayer polymer structure and forming capacitor plates on the polymeric membranes encapsulating the cavity. Measuring the capacitance change induced by changes in the embedding pressure (which cause changes in the positions of the bounding polymeric membranes) enables calculation of the pressure. The use of polymeric membranes requires understanding the leakage rate of gas into the reference cavity, which is a source of pressure drift. Developing a polymer-based pressure sensor that solves the problem of sensor drift as a result of gas permeation entails the fabrication of a silicon pressure reference cavity embedded in the polymer substrate, which results in a more hermetic and lower drift sensor while preserving the flexibility of the embedding polymer. Both wired and wireless versions of pressure and flow sensors of these types were developed and characterized. Further, the sensors were characterized on airfoils and their performance in a wind tunnel was determined.

Figure 1. Structure and content of the research
CHAPTER 1

INTRODUCTION

1.1 Objective

Human beings have always been amazed by how easily birds can fly. Hummingbirds can hover while flapping their wings in one position at a rate as high as 80 times per second [1]. Bar-tailed godwits can fly 11,000 km nonstop to migrate from Alaska to New Zealand [2]. To investigate the flight capability of birds, researchers train pigeons to fly in a wind tunnel and observe their behavior as the flow rate varies [3]. These researchers found that as wind velocity increases, the pigeons greatly reduce their wing span and area, which in turn greatly reduces wing profile drag [3]. These birds demonstrate extraordinary capability to adapt to flow variation by adjusting their wings, which also suggests that they have the ability to sense flow variation. Research on the sensory system of birds shows that mechanoreceptors surround the feather follicles of birds, which sense airflow over their wings [4]. Furthermore, the sensing system is able to detect the stall and separation of the airflow on the surface of the wings [4].

Human beings have always envied the fact that birds can fly. To achieve this goal, human beings have invented different kinds of flight contraptions, from the kite, invented by the ancient Chinese, to the world’s first successful airplane, invented by the Wright Brothers. The aeronautics industry has also developed pilotless aircraft, that is, the unmanned aerial vehicle (UAV) for various applications. For instance, one kind of UAV recently launched by Amazon delivers products. As the industry produces more and more
of such vehicles, we may, in the near future, see UAVs flying around our homes and in public areas.

A dream of UAV researchers in both academia and the aeronautics industry is to develop a UAV that flies like a bird. To achieve this goal, they must develop sensors in the UAV that provide extraordinary sensing capability. The two critical parameters to sense are pressure and flow rates. When air flows across an airfoil, the top flow accelerates, and therefore the pressure above the airfoil is lower than the bottom pressure, which results in lift force. The pressure and flow distribution on an airfoil of a UAV flying in the atmosphere will be more complicated because of factors such as turbulence and flow separation.

For birds, mechanoreceptors around feather follicles are their flow sensors; these sensors cover the entire area of birds’ wings with high density. For achieving similar flow sensing ability/resolution in a UAV, tiny sensors are needed to cover whole airfoils. Advances in microelectronics and micromachining technologies make it possible to fabricate these tiny flow sensors, which can be placed on the airfoil to measure air flow and pressure. Furthermore, these sensors should be small enough so that they only minimally disturb the flow on the airfoil. The concept of the flow sensors for velocity and pressure measurement is demonstrated in Figure 2. MEMS flow sensors fabricated and/or assembled on a flexible substrate are mounted on a curved airfoil to measure flow and pressure changes around the airfoil.
1.2 Background

1.2.1 Flight Control with Flow Sensors and Actuators

Flow information helps a pilot to maneuver an airplane. For instance, the air pressure suggests the height of the airplane; the flow rate relates lift and drag of the flight. In an airplane, the flow is generally measured by a Pitot tube, which was invented in the 18th century and named after its inventor, Henri Pitot, a French engineer. A simple Pitot tube is illustrated in Figure 3. The tube points directly into the air flow and the pressure inside the tube can be measured. The measured pressure is called stagnation pressure of the flow or total pressure, which is the sum of static pressure and dynamic pressure according to Bernoulli’s equation:

\[
P_{\text{total}} = P_{\text{static}} + P_{\text{dynamic}} = P_{\text{static}} + \frac{1}{2} \rho v^2. \tag{1.1}
\]

If static ports are opened on a Pitot tube and static pressure is measured, the flow velocity can be determined by the dynamic pressure, which is the difference between total
pressure and static pressure. For UAV application, especially when a UAV is small, deploying a Pitot tube becomes challenging. In addition, in the application of airfoil flow and pressure mapping (Figure 2), placing multiple Pitot tubes for measuring flow and pressure distribution on an airfoil seems impractical unless it is miniaturized.

Figure 3. Schematic of a Pitot tube with a static port

MEMS technology is concerned with miniaturization. The key to miniaturization is photolithography, where small features on a glass mask are transferred to a photosensitive polymer (photoresist) mask coated on a device substrate through UV exposure. Different etching techniques such as reactive ion etching (RIE), inductive-coupled plasma (ICP) etching, and various kinds of wet etching processes have been developed to release the sensor structure. Once the device structure is fabricated, thin metal films are often sputtered or evaporated to interconnect the device structure with circuits or other interface blocks.

From the first high-volume commercial silicon piezoresistive MEMS pressure transducer\[5\], researchers have miniaturized hundreds and thousands of sensors, actuators, and electromechanical systems. These miniaturized/MEMS devices have found
wide application in many fields. For instance, MEMS gyroscope is a key component in today’s consumer electronics market. A MEMS accelerometer is inside every modern automobile to detect acceleration for safety control. MEMS technology also makes flow sensors more useful not only in traditional process control and metrology [6] but also in flight control applications involving unmanned aerial vehicles.

Figure 4 shows a flexible PCB-based hot-wire flow sensor system, which indirectly measures flow velocity [7]. The sensors have been successfully mounted on the airfoil of a UAV and detected flight parameters such as airflow speed and angle of attack [7].

Figure 4. A flexible PCB-based hot-wire flow sensor system for UAV control reported in [7]

Figure 5 shows a PCB-based capacitive flow sensor array for detecting aircraft angle of attack and air speed by measuring the aerodynamic pressure [8].
A piezoresistive shear stress sensor is demonstrated in Figure 6 [9]. The sensors are mounted on an airfoil to monitor flow separation [9].

Figure 6. A piezoresistive shear stress sensor for flow separation detection reported in [9]

Figure 7 shows the implementation of control system in a micromechanical flying insect [10]. Flow sensors provide information for the flight mode stabilizer and the force sensors at wing bases help control wing trajectory [10]. Once the control system receives
flow information from the sensors, the system will command actuators to maneuver the UAV and/or controls the flow.

![Diagram of flight control architecture](image)

**Figure 7.** Design architecture for the control unit of a micromechanical flying insect reported in [10]

MEMS technology also helps the development of miniaturized actuators for flow control. For instance, a MEMS synthetic jet actuator is shown in Figure 8 [11]. The actuator comprises a cavity with a hole. The flexible membrane draws the air around the hole with low momentum (Figure 9 (a)) and expels the air with high momentum (Figure 9 (b)), which can reattach a separated flow [11, 12]. In Chapter 2, an experimental setup will include a synthetic jet for flow reattachment.
Other than the synthetic jet actuator, MEMS actuators such as micro-jet engines [13], micro-nozzles [14], and microthrusters [15] have also been developed [16]. This large variety of actuators gives UAV designers the flexibility to choose suitable actuators to control the flow and maneuver UAVs. Figure 2 illustrates the objective of this research: MEMS flow sensors covering the airfoil for flow and pressure measurements. However, ultimately, on the airfoil, there will be not only MEMS sensors but also MEMS actuators. The combination of both will allow a UAV to fly like a bird.
1.2.2 MEMS Flow Sensors

Flow sensors are widely used in both industry and research. Many applications, including flow sensing for UAVs, call for tiny flow sensors. Therefore, MEMS-enabled flow sensors are the subject of much research activity. The best flow sensors are developed in nature. For instance, mechanoreceptors surrounding the feather follicles of birds are able to detect the stall and separation of the airflow on the surface of the wings [4]. The lateral line of a fish detects tiny water velocity changes on its skin that occur when the fish passes nearby obstacles[17]. The filiform hairs of crickets are flow sensors, which respond to movement energies on the order of $10^{-21}$ Joule [18]. Therefore, researchers can learn from nature how to develop high performance biomimetic flow sensors.

Biomimetic flow sensors generally comprise a cantilever beam exposed in the flow, and a sensing element detecting the motion of the cantilever in the flow. These sensors can be categorized by their sensing principles, which include thermal, capacitive, piezoresistive, piezoelectric, optical, and magnetic. Among these sensors, thermal, capacitive and piezoresistive flow sensors will be discussed in the following paragraphs.

A thermal flow sensor is often called a hot wire, which is a heated wire made out of resistive materials such as metal and silicon. This heated sensing element will cool down through convection when air flow passes. The higher the flow rate is, the more heat loss will be present in the hotwire. This heat loss results in a resistance change in the sensing element. A servo loop monitors this resistance change, controls the heating of the sensing element, and detects the flow rate. For instance, in the hotwire flow sensor for the UAV application described in Figure 4, a servo loop maintains the sensor temperature by
sensing the sensor resistance through a Wheatstone bridge and varying the supply voltage of this bridge [7]. Many commercially available flow sensors are also based on this technique because of the accuracy and reliability of hot wire sensors. A hot wire flow sensor (Omega FMA-605-I) will be used in the flow sensor measurement in this research as a reference sensor. However, the power consumption of the hot wire flow sensor is high because the servo loop of the sensor needs to apply a current for heating the sensor. A hot wire flow sensor with power consumption in the milliwatt range may not suitable for many low power applications in which microwatt power consumption is desired; this is especially true for array applications where many such sensors may be needed.

In a capacitive biomimetic flow sensor, the cantilever beam motion in the flow is translated into a capacitance change. The Transducer Science and Technology group in University of Twente, Netherlands has developed a series of bio-mimetic capacitive flow sensors with high sensitivity [19-22]. For instance, the bio-mimetic capacitive flow sensor array with high-aspect ratio SU-8 pillars in Figure 10 is able to sense flow on the order of 1mm/s [20]. The sensing principle of the capacitive flow sensor is shown in Figure 10. When an air flow passes across the SU-8 pillar, a drag will tilt the pillar, which results in a differential capacitance change [20]. The researchers developed a surface micromachining process for the sensor fabrication [20]. The SU-8 pillar (Figure 11 (V)) sits on the aluminum (Al) electrodes (Figure 11 (IV)). The membrane/torsional beam (Figure 11 (III)) underneath the Al electrodes is a low pressure chemical vapor deposition (LPCVD) silicon rich nitride layer. The sacrificial layer (Figure 11 (VI)) is deposited by LPCVD of polysilicon. Similar capacitive biomimetic flow sensors with a hair-like pillar
and capacitive sensing elements have been developed both for air flow sensing and for liquid flow sensing [23, 24].

Figure 10. Bio-mimetic Si-based capacitive flow sensor with SU-8 cantilever as a microtuft [20]

![Bio-mimetic Si-based capacitive flow sensor](image)

Figure 11. Fabrication process of the capacitive flow sensor [20]

![Fabrication process of the capacitive flow sensor](image)

In a piezoresistive flow sensor, the sensing element, which senses the motion of the sensor cantilever, is a piezoresistor. The piezoresistive effect was first discovered by
Lord Kelvin and he found that under mechanical strain, the electrical resistance of copper and iron wires changed [25]. This factor also applies to other metals and metal alloys, which are often used to fabricate strain gauges. When a strain gauge is attached to a structure experiencing strain changes, the strain gauge will transduce strain changes into resistance changes. Figure 12 illustrates a schematic of a piezoresistive strain gauge, which is usually a strip of piezoresistive material, which is often called a piezoresistor. When the piezoresistor experiences strain, its resistance will change. The ratio between the resistance change and the strain is called Gauge Factor (GF). Equation (1.2) shows the relationship between strain and resistance in a strain gage:

$$\frac{\Delta R}{R_0} = G \varepsilon,$$

(1.2)

where $R_0$ is the initial resistance, $\Delta R$ is the resistance change, $G$ is the Gauge Factor, and $\varepsilon$ is the strain. Table 1 displays the GF of some metals and metal alloys [26]. Among these metals, Platinum (Pt) shows the highest GF. Furthermore, being a noble metal, the stable material property may translate to a stable/low-drift sensor output when it is used as a piezoresistor in a sensor.

![Figure 12. Schematic of a piezoresistive strain gauge](image)
Table 1. Gauge Factor of different metals and metal alloys [26]

<table>
<thead>
<tr>
<th>Metal</th>
<th>GF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platinum (Pt 100%)</td>
<td>6.1</td>
</tr>
<tr>
<td>Isoelastic (Fe 55.5%, Ni 36%, Cr 8%, Mn 0.5%)</td>
<td>3.6</td>
</tr>
<tr>
<td>Constantan/Advance/Copel (Ni 45%, Cu 55%)</td>
<td>2.1</td>
</tr>
<tr>
<td>Nichrome V (Ni 80%, Cr 20%)</td>
<td>2.1</td>
</tr>
<tr>
<td>Monel (Ni 67%, Cu 33%)</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Wang et.al. reported a Pt piezoresistive flow sensor in 2007 [27]. The sensor can also be categorized as a bio-mimetic flow sensor, which consists of an out-of-plane cantilever and a Pt piezoresistor to monitor the cantilever motion in the flow. When flow passes across the cantilever, the cantilever beam will bend, resulting in a tensile strain on the piezoresistor. This strain change will induce an increase of the resistance in the Pt piezoresistor.

![Figure 13. A Pt piezoresistive flow sensor; left: schematic illustration; middle: top-view of the sensor; right: side-view of the sensor reported in [27]](image)

Other than metal, silicon is also a widely used material as a piezoresistor in piezoresistive sensors. In 1954, Charles Smith at Bell Laboratories, found piezoresistivity in silicon and germanium [28]. With a gauge factor an order of magnitude higher than its metal counterparts [28], perfect elasticity [29], and well developed process tools and technology, silicon has become a first choice of the material for strain gauge fabrication. However, a main challenge of silicon is that it is a brittle material [30], which limits its
applications where flexibility is necessary. Despite this limitation, silicon piezoresistive flow sensors, because of the stable material properties of silicon, are still developed and utilized by researchers and engineers. For example, the MedX lab at Northwestern University developed a series of highly sensitive silicon piezoresistive flow sensors [31-33], a representative of which is shown in Figure 14. The sensor comprises an SU-8 cilium and an in-plane cantilever with a boron ion-implanted piezoresistor at the bottom of the cantilever [32]. The cantilever will bend when the SU-8 cilium tilts as a result of its drag in the air flow. This flow-induced cantilever motion is then monitored by the silicon piezoresistor. Because of the high gauge factor of the silicon piezoresistor (33.6-78.9), the sensor is able to detect a flow rate below 1 mm/s in water [32]. Illustrated in Figure 15, the sensor fabrication process starts with a boron implantation of the piezoresistor on an SOI wafer, followed by metal interconnection with a lift-off process. The in-plane structure is fabricated by a series of silicon dry etching steps. Then a high aspect ratio SU-8 cilium is fabricated by spin-coating SU-8 epoxy at a low spin rate.

Figure 14. A silicon piezoresistive air flow sensor with SU-8 cilia reported in [32]
Figure 15. Fabrication process of the silicon piezoresistive sensor reported in [32]

Figure 16 illustrates two types of bio-mimetic flow sensors proposed by Ozaki et. al. in 2000 [34]. Figure 16 (a) shows the 1-Degree of Freedom (1-DOF) flow sensor, with a cantilever protruding in the flow and a piezoresistor monitoring the cantilever bending as flow rate varies. The 2-DOF sensor illustrated in Figure 16 (b) has a cantilever beam, which sits on two cross-shaped and fixed strips, and piezoresistors on fixed ends of each strip. The tilt of the cantilever in air flow will result in a strain change in the strips, which causes resistance variation in the piezoresistors. After the development of 1-DOF or 2-DOF flow sensors by Ozaki et. al., various bio-mimetic sensors were reported with similar operation principles but different geometry, material, and fabrication process [35], such as bio-mimetic flow sensors reported in [27, 36-39].
The aforementioned sensors are mostly silicon-based sensors. Although these sensors demonstrate good performance, they require relatively complex fabrication sequences; furthermore, being silicon-based, these sensors are not able to cover large areas of vehicle wings without tiling or similar approaches. By contrast, polymer-based sensors have been successfully demonstrated and applied to non-planar structures such as a UAV. An example is the hotwire flow sensor built on a flexible PCB shown in Figure 4. Researchers have also developed polymer-based piezoresistive sensors for flow sensing. For example, Figure 17 shows an example of the polymer-based piezoresistive sensor reported in [40]. The sensor can be used for tactile sensing; however, theoretically the sensor could sense flow as well with the movable pillar and elastomeric sensing elements[35]. The pillar is made out of polyurethane, and the piezoresistors sitting on the bottom of the pillar are carbon-black-loaded polyurethane, which is made by mixing the
elastomer resin, curing agent, and 30% (by weight) carbon black above the percolation threshold [40, 41]. Compared to silicon-based flow sensors, the development of the fabrication process is often more challenging and unconventional because few developed processes can be borrowed from the IC industry, which is mainly silicon-based. Figure 18 shows the fabrication process of this polymer-based flow sensor: photoresist mold patterning of carbon black-loaded polyurethane followed by wax-molded polyurethane assembly and curing [40].

Figure 17. The polymer-based piezoresistive sensor reported in [40]

Figure 18. The fabrication process of the polymer-based flow sensor in [40]
In the MSMA research group at the Georgia Institute of Technology, we have also demonstrated an out-of-plane micromachined flexible piezoresistive all-polymer flow sensor array based on flex-PCB technologies [38]. Although the sensor provided a large output without complex sensing circuitry for compensation and amplification of the sensor output, a significant resistance drift in the sensor output was observed (Figure 19) [38], potentially limiting the applicability of the sensor.

![Flow induced vibration and sensor output](image)

**Figure 19.** Flex-PCB-based bio-mimetic air flow sensor and sensor output [38]

### 1.2.3 MEMS Pressure Sensors

The MEMS pressure sensor itself is a billion-dollar market [42], because of its wide applications in various fields such as biomedical [43], automobile [44], and aerospace [8]. A MEMS pressure sensor senses pressure with a deformable membrane. The membrane deflects as a result of pressure difference between each side of the membrane. By monitoring the deflection of the membrane with sensing elements, this pressure difference can be measured. To measure an absolute pressure, a hermetically sealed cavity is needed. This cavity can comprise vacuum or can be filled with gas at a
certain pressure. In the piezoresistive flow sensor, the piezoresistor monitors the cantilever beam motion in the flow. A similar principle can also be applied to pressure sensing. By placing piezoresistors on the edge of the membrane, where the maximum strain occurs, the deflection of the membrane can be translated to a resistance change. Piezoresistive pressure sensor evolves with advances of micromachining technology. The first commercial pressure sensor was released in 1958 with a metal membrane and silicon piezoresistive strain gauge [5]. It was then replaced by all-silicon pressure sensors with a silicon membrane and diffused piezoresistors [42]. Figure 20 is a figure in a review of capacitive flow sensors by Eaton et.al., which is adapted from [5], demonstrating how the piezoresistive pressure sensors evolve with the development of micromachining technologies.
In a piezoresistive pressure sensor, the deflection of the membrane of the device is measured by piezoresistors. If we can monitor the deflection of the membrane by itself, then the piezoresistors on the membrane can be abandoned, which brings simplicity in sensor design and fabrication. This idea is fulfilled by capacitive pressure sensing. Figure 21 shows the sensing principle of a capacitive flow sensor, which translates the pressure difference into capacitance variation. Assuming both top membrane and the area of the bottom substrate underneath are conductive, when the membrane of the capacitive pressure sensor deflects as a result of pressure difference, the capacitance between top and bottom membrane will change. The capacitance change is inversely proportional to
the distance between top membrane and the substrate, which reflects the pressure difference.

Figure 21. Sensing principle of a capacitive pressure sensor

The development and fabrication of the capacitive pressure sensor also benefits greatly from advances in micromachining technology, especially bonding technology. Direct silicon bonding, or silicon fusion bonding (SFB), was reported in 1985 [45] for SOI wafer fabrication. SFB is the direct bonding of two single-crystal silicon wafers and the surface of the silicon wafers can be with or without thermally grown oxide [46]. The chemical reaction during the SFB is described in [45]:

\[
Si - OH + OH - Si \rightarrow H_2O + Si - O - Si
\]  

(1.3)

Four key elements for SFB are surface cleanliness, flatness, hydration, and high temperature [46]. To fulfill these requirements, the process of the SFB generally includes surface cleaning and activation such as RCA cleaning, HF, and O\(_2\) activation; bonding, which is generally done in a bonder with pressure and heat; and annealing at a high temperature [47]. To achieve a bonding strength close to that of bulk silicon, the annealing temperature requires approximately 1000\(^\circ\)C for HF and RCA activation [47]. However, O\(_2\) plasma treatment of the bonding surface can lower this annealing temperature to 300\(^\circ\)C while still maintaining a bonding strength close to that of bulk
silicon [47]. Soon after the first report of the SFB, this bonding method was quickly applied to pressure sensor fabrication [48]. Compared to wafers bonded by other processes such as anodic bonding, the fusion-bonded silicon wafers have no mismatch of thermal expansion coefficient (TEC). Compared to the surface-micromachined pressure sensor, fusion-bonded pressure sensors have high piezoresistive sensitivity, less residual strains, and minimal thermal mismatch [46]. With all these merits, fusion-bonded pressure sensors have been studied and developed [48, 49]. Figure 22 demonstrates an absolute pressure sensor fabricated using SFB [50]. The silicon substrate and the silicon dioxide spacer of the sensor are from one silicon wafer, while the top membrane is from another silicon wafer, which is fusion bonded with the first wafer, and released with silicon wet etching [50]. The fabricated pressure sensor can operate in touch mode, that is, the top membrane touches the bottom substrate, which improves the linearity of the sensor response [50].

![Diagram of a pressure sensor](image)

**Figure 22. Touch-mode pressure sensor fabricated using SFB reported in [50]**

As described in the previous section, despite lower specific sensor performance, polymer-based sensors have certain advantages over their silicon-based counterparts.
Therefore, polymer-based pressure sensors are the subject of much research. Figure 23 shows the cross-sectional view of a polymer-based biodegradable pressure sensor [51]. To achieve biodegradability, single crystal silicon is excluded from the choices of materials. The materials which compose the biodegradable sensor are biodegradable polylactic acid (PLA) as a dielectric material for the spacer, and zinc as a conductive material for the top and bottom membrane electrodes [51]. The fabrication of the sensor is again unconventional: the PLA substrate with plated zinc wires is folded and laminated with a PLA spacer between the top and bottom membranes [51].

![Figure 23. Cross-sectional view of the biodegradable pressure sensor reported in [51]](image)

For an absolute pressure sensor, a hermetically sealed cavity as pressure reference is critical. If the pressure in the cavity varies as a result of leakage, the internal pressure change will reflect to the measured external pressure as an error or drift. Silicon is suitable for maintaining the hermeticity of the cavity, which results in a stable/low drift sensor output in a capacititive pressure sensor [52]. Polymer materials, however, are typically not hermetic, allowing gas to penetrate under a pressure difference between each side of the material as illustrated in Figure 24. The permeability coefficient \( k \) describes the ability of gas to penetrate through a polymeric membrane [53]:

\[
k = \frac{q_t}{A \Delta p}, \quad (1.4)
\]
where \( q \) is the mass flux of gas, \( A \) is the membrane area, \( \Delta p \) is the pressure difference, and \( t \) is the membrane thickness. In the biodegradable sensor reported in [51], \( \text{N}_2 \) and \( \text{O}_2 \) permeate the PLA with a permeability of 0.05 and 0.26 Barrer [54]. The gas permeation will result in a pressure change in the sensor cavity and therefore a sensor drift, which may or may not be important given the sensitivity and lifetime of the sensor.

Figure 24. Illustration of gas molecules penetration through a polymer membrane

1.2.4 Wireless Sensors

In sensor applications, wireless sensing is always appealing and for certain applications, wireless sensing is required. For example, if the biodegradable sensor in [51] is to be implanted in the human body the sensor needs to be wireless. The wireless sensing principle of this sensor is based on LC resonance. As illustrated in Figure 25, a capacitive pressure sensor and an inductor form an LC resonator that responds to pressure differences. When pressure changes, the capacitance of the pressure sensor varies, which
results in a shift in the resonant frequency of the LC resonator. LC resonator-based passive wireless pressure sensors have been implanted to monitor heart pressure (Figure 26) [43]. A wireless system composed of a silicon micromachined pressure sensor and an inductor has been fabricated to continuously monitor intra-ocular pressure (Figure 27) [55].

Figure 25. Sensing principle of the polymer-based biodegradable absolute pressure sensor reported in [51]

Figure 26. Fabricated flexible wireless passive pressure sensor reported in [43]
Figure 27. A wireless system for intra-ocular pressure measurement reported in [55]

A passive sensor needs a signal to interrogate the device and reflect the signal back with sensing information. A great benefit of a passive sensor is that it does not require an internal power source. However, it lacks the capability to pre-process signals. Furthermore, in an array application, interference between sensors may occur. Active wireless sensors, however, have the ability to run algorithms and send the processed signal out when it is ready. In an array application, a multiplexer can resolve the issue of interference by selecting one sensor at a time.

The aforementioned LC-resonator based passive pressure sensors can be turned into an active pressure sensor by incorporating active devices such as a tunnel diode. As shown in Figure 28, an active wireless pressure sensor is used for high temperature pressure sensing and communication applications [56]. By biasing the tunnel diode in its negative resistance region, the circuit will oscillate at the resonant frequency of the LC resonator. The benefit of using a tunnel diode is that the supply voltage can be in the hundred mV range [56]. However, if a supply voltage can be high enough, for example, a 3.3 volt power supply for powering many commercially available CMOS silicon chips, any circuitry that converts the sensor output into a frequency variation can turn the passive sensor wireless sensor into an active one [57]. If the interface circuitry includes a
microcontroller, the capability of the active sensor system can be greatly extended, for instance, to signal processing [58].

Figure 28. An active wireless sensor architecture [56]

1.3 Research Focus

Since physical flexibility is a key feature for the UAV application, my research will focus on polymer-based flow sensors. It is more challenging to develop the MEMS process for polymer sensors than it is for their silicon counterparts. The silicon process has been intensively studied and developed in the integrated circuit (IC) industry, where most ICs are silicon-based. To develop silicon-based sensors, researchers can borrow technologies and tools developed for IC fabrication. However, to develop polymer-based sensors, researchers do not have as many resources available and sometimes have to start from scratch and at the same time, ensure that cost and performance are competitive. Polymer materials are typically inexpensive compared to silicon wafers. However, for polymer-based sensors, if the fabrication process is complex and/or fabrication time is
too long, the total cost could still be higher than that of a silicon-based sensor. Thus, lowering cost and increasing yield requires a simple fabrication process.

In addition to cost and fabrication issues, polymer-based sensors suffer from drift issues as mentioned above. One cause of drift is environmental change such as temperature variation. In this case, if the temperature is monitored, drift in the polymer sensor can be compensated for. However, polymer materials are much less stable than silicon. Therefore another cause of drift is aging and viscoelasticity. In addition, since these causes of drift are time-dependent, traditional drift compensation methods such as temperature compensation are not sufficient. Therefore, to develop a polymer sensor, a challenge will be to solve the drift issues.

The development of wireless polymer-based sensors could be useful in UAV applications. After all, both flow and pressure sensors should be mounted on the airfoil. Wireless sensors would allow us to avoid drilling holes on the airfoil. Because of the benefits of active wireless sensors over passive ones discussed in the previous section, in this research, active sensor systems will be developed.
CHAPTER 2

ALL-POLYMER AIR FLOW SENSORS

In the application shown in Figure 2, the flow sensors will be mounted on an airfoil, which is a curved surface. Since the sensors are exposed for flow measurement, these sensors may experience shocks and large bending. For instance, the airfoil might touch the leaves of a tree or grass on the land during flight. Therefore, flexibility becomes vital to the flow sensor. Therefore, a flow sensor must be constructed out of flexible material. The conventional material used for constructing the flow sensor has been silicon. However, silicon is a brittle material, and a silicon wafer is easy to break. Because of these features, it is not the ideal material. Therefore, flow sensors for the UAV application have been made of all-polymer material.

The research in this chapter begins by examining the all-polymer flow sensor described in [38] and aims at reducing its drift by increasing its sensitivity. This research involves the development of a highly sensitive sensor. Because the original flow sensor had a relatively short cantilever beam, this study begins by introducing a long cantilever beam. To increase the sensor array density and simplify the fabrication process, a dual-cantilever sensor with both small length and high sensitivity was fabricated. Furthermore, to reduce the time for large array fabrication, laser micromachining was replaced by RIE in the sensor fabrication.
2.1 An Improved-Sensitivity Single-Cantilever All-Polymer Air Flow Sensor

2.1.1 Theoretical Analysis

In [38], the authors demonstrate an all-polymer flow sensor (Figure 29) that is both flexible and scalable. The sensor comprises an out-of-plane cantilever beam made out of Kapton® (Dupont) and a composite piezoresistor, a carbon-black-loaded polydimethylsiloxane (PDMS) piezoresistor (Elastosil® LR3162, Wacker Chemie AG), on the bottom of the cantilever. The sensor is built on a flexible printed circuit board (PCB), and its out-of-plane structure is formed by a stress gradient that occurs and builds during fabrication when a silicon dioxide layer is deposited on the backside of the cantilever.

![Figure 29. An all-polymer flow sensor [38]](image)

Figure 30 shows the sensing principle of the piezoresistive all-polymer flow sensor. The sensor, with an out-of-plane Kapton® cantilever, bends when protruding into the air flow. Air flow across the microtuft causes the deformation of the microtuft. The
deformation, which is proportional to the distributed force on the microtuft, in turn, induces the strain in the piezoresistor. The resistance of the piezoresistor, therefore, changes as a function of the strain induced by the applied wind velocity [27]. The sensor in response demonstrates a baseline resistance drift, described in Figure 19. The drift greatly impairs the sensor precision in the flow measurement.

The sensor structure is modeled as a cantilever beam with a uniform load $P_{\text{wind}}$, which is induced by air flow. In our application, the flow rate across the airfoil is much lower than speed of sound, therefore, Bernoulli’s equation is still valid [59], with

$$P_{\text{wind}} = \frac{1}{2} \rho_{\text{air}} V^2, \quad (2.1)$$

where $\rho_{\text{air}}$ is the density of air, and $V$ is the flow velocity. The maximum deflection (deflection at the tip of the cantilever) is given by [60]

$$D_{\text{max}} = \frac{l^4}{8EI} q, \quad (2.2)$$

where $l$ is the length of the cantilever, $E$ is the Young's modulus of the cantilever, and $I$ is the moment of inertia, which is given by
\[ \ell = \frac{wt^3}{12} \tag{2.3} \]

where \( w \) is the width and \( t \) is the thickness of the cantilever, and \( q \) is the uniform load intensity, given by:

\[ q = P_{\text{wind}} \times w, \tag{2.4} \]

with units of N/m.

Therefore:

\[ D_{\text{max}} = \frac{3l^4}{2Et^3} P_{\text{wind}} \tag{2.5} \]

The bending of the cantilever induces a stress on the cantilever. The maximum stress is on the bottom of the cantilever, which is:

\[ \sigma_{\text{max}} = \frac{l^2t}{4l} P_{\text{wind}} w. \tag{2.6} \]

Therefore, the maximum strain is:

\[ \varepsilon_{\text{max}} = \frac{3l^2}{Et^2} P_{\text{wind}} \tag{2.7} \]

The polymer piezoresistor is located at the bottom of the cantilever, where the strain is at its maximum. Once a piezoresistor experiences a strain change, the resistance will change accordingly. The resistance of the unstrained piezoresistor is calculated by:

\[ R = \rho \frac{l}{A} = \rho \frac{l}{wt}, \tag{2.8} \]

where \( \rho \) is the resistivity of the piezoresistor. If we assume the resistor experiences a strain \( \varepsilon \), then the width and the thickness of the piezoresistor become:

\[ w' = (1 - \nu \varepsilon)w \tag{2.9} \]
\[ r' = (1 - \nu) r, \quad (2.10) \]

where \( \nu \) is the Poisson ratio. Therefore,

\[ \frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \varepsilon(1 + 2\nu), \quad (2.11) \]

The following matrix equation relates the relative resistivity change \( \Delta \rho / \rho_0 \) to the stress \( \delta \).

\[
\begin{bmatrix}
\Delta \rho_1 / \rho_0 \\
\Delta \rho_2 / \rho_0 \\
\Delta \rho_3 / \rho_0 \\
\Delta \rho_4 / \rho_0 \\
\Delta \rho_5 / \rho_0 \\
\Delta \rho_6 / \rho_0
\end{bmatrix}
=
\begin{bmatrix}
\pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\
\pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\
\pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\
0 & 0 & 0 & \pi_{44} & 0 & 0 \\
0 & 0 & 0 & \pi_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & \pi_{44} & 0
\end{bmatrix}
\begin{bmatrix}
\delta_1 \\
\delta_2 \\
\delta_3 \\
\delta_4 \\
\delta_5 \\
\delta_6
\end{bmatrix}.
\quad (2.12)
\]

If the length of the piezoresistor is along the x direction, then [61]:

\[ \rho_x = \pi_{11} \delta_x + \pi_{12} \delta_y + \pi_{12} \delta_z. \quad (2.13) \]

If the uniaxial tension stress condition applies (\( \delta_x \neq 0, \delta_{y,z} = 0 \)), then [61]

\[ \rho_x = \pi_{11} \delta_x = \pi_{11} E' \varepsilon_x. \quad (2.14) \]

where \( E' \) is the Young’s modulus of the piezoresistive material. Combining (2.11) and (2.14) yields:

\[ \frac{\Delta R}{R} = (\pi_{11} E' + 1 + 2\nu) \varepsilon_x. \quad (2.15) \]

The piezoresistor is located on the bottom of the cantilever, where the maximum strain occurs; therefore,

\[ \frac{\Delta R}{R} = (\pi_{11} E' + 1 + 2\nu) \varepsilon_{\text{max}} = (\pi_{11} E' + 1 + 2\nu) \frac{3l^2}{Et^2} p_{\text{wind}}, \quad (2.16) \]
The block diagram in Figure 31 concludes the flow of the theoretical analysis of the sensor. However, this sensor model did not include two effects. The first effect is the reduction of the force of the flow resulting from the curvature of the cantilever. The second effect is the strain induced by the thermal mismatch between the Kapton® film and the silicon dioxide deposited on the back of the Kapton® film. To account for these two effects while still maintaining the simplicity of the model, the cantilever model of the sensor is revised with an effective cantilever length $l_{\text{eff}}$ and a piezoresistor with an initial strain. The effective length of the cantilever is defined by the maximum deflection of the cantilever, that is, the distance from the tip of the curved cantilever to the sensor substrate. With the initial deflection of the cantilever $l_{\text{eff}}$, the initial strain on the bottom of the cantilever is:

$$\varepsilon_{\text{ini}} = -\frac{2t}{l^2} l_{\text{eff}}, \quad (2.17)$$

where the negative sign represents a compressive strain. Therefore, Equation (2.16) becomes:

$$\frac{\Delta R}{R} = (\pi_1 E' + 1 + 2\nu)(\varepsilon_{\text{max}} - \varepsilon_{\text{ini}}) = (\pi_1 E' + 1 + 2\nu)(\frac{3l_{\text{eff}}^2}{Et^2}) P_{\text{wind}} - (\pi_1 E' + 1 + 2\nu) \frac{2t}{l^2} l_{\text{eff}}, \quad (2.18)$$

To simplify the model, we can reflect the initial strain $\varepsilon_{\text{ini}}$ into the initial resistance of the piezoresistor $R_0$, that is, the resistance of the piezoresistor with the sensor out-of-plane cantilever released. Therefore,
\[ \frac{\Delta R}{R_0} \approx (\pi_1 l E' + 1 + 2\nu) e_{\text{max}} = (\pi_1 l E' + 1 + 2\nu)\left(\frac{3l_{\text{eff}}^2}{Et^2}\right)p_{\text{wind}}, \]

where \( \Delta R \) is now the resistance change with \( R_0 \) as the baseline resistance. Substituting \( P_{\text{wind}} \) with \( \frac{1}{2} \rho_{\text{air}} V^2 \), Equation (2.19) yields

\[ \frac{\Delta R}{R_0} \approx \frac{1}{2} (\pi_1 l E' + 1 + 2\nu)\left(\frac{3l_{\text{eff}}^2}{Et^2}\right)\rho_{\text{air}} V^2, \]

Therefore,

\[ \frac{\Delta R}{R_0} = SV^2, \]

where the coefficient \( S \) is given by

\[ S = \frac{1}{2} (\pi_1 l E' + 1 + 2\nu)\left(\frac{3l_{\text{eff}}^2}{Et^2}\right)\rho_{\text{air}} \cdot \]

Since the coefficient \( S \) is related the sensitivity the sensor, \( S \) will be called the coefficient of sensitivity.

The sensor mechanical resonant frequency is estimated using the following formula:

\[ f = \frac{3.52}{2\pi} \sqrt{\frac{EI}{u_1 l^4}}, \]

where \( E \) is the Young’s modulus of the Kapton® film, \( I \) is the moment of inertia, and \( u_1 \) is the product of the density of the Kapton® film and the cross-sectional area of the cantilever-like microtuft [62]. The estimated resonant frequency is approximately 130Hz. This parameter is important in determining the sampling frequency of the sensor output for the vibration amplitude measurement method that will be discussed in Chapter 4.
2.1.2 Drift Reduction by Sensitivity Enhancement

The sensitivity of the sensor $K$ is defined as

$$K = \frac{\Delta R}{R_0 V}, \quad (2.24)$$

where $V$ is the wind velocity and $\Delta R$ is the resistance change when the wind velocity is $V$. The sensitivity $K$ is related to the coefficient $S$ as

$$K = SV \quad (2.25)$$

If the sensor has a baseline resistance drift of $\Delta R_d$, this drift could be referred to as drift in wind velocity $V_d$, which is the wind-velocity-referred baseline drift of the sensor. Equation (2.26) yields the value of $V_d$.

$$V_d = \frac{\Delta R_d}{R_0 K} \quad (2.26)$$

If we assume that a baseline resistance drift occurs and the value $\Delta R_d/R_0$ is large with large sensitivity $K$, the sensor still has small drift $V_d$. In the extreme case that $K$ is infinite, regardless of how large the baseline resistance drift is, the wind-velocity-referred-drift $V_d$ becomes zero (of course, the dynamic range of the sensor also shrinks).

For two sensors with the same baseline resistance drift $\Delta R_d/R_0$, if sensitivity $K$ of one sensor is $m$ times as large as the other, then the wind velocity-referred drift of this sensor will be $m$ times as small. Therefore, one solution to overcoming sensor drift is to increase the sensitivity of the sensor, subject to dynamic range reductions as discussed above.

Equation (2.16) shows that the sensitivity of the sensor is proportional to $l_{\text{eff}}^2$, and inversely proportional to $t^2$. Therefore, a sensor with high sensitivity translates to a
sensor with a long and thin cantilever beam. For the improved sensitivity flow sensor, the cantilever is as long as possible (3.5mm) within fabrication constraints, which will be discussed in the sensor fabrication section. The sensor width is set as 0.6mm, which allows better alignment. Table 2 compares the sensor dimension of the all-polymer flow sensor in [38].

Table 2. Sensor dimension variation to achieve higher sensitivity

<table>
<thead>
<tr>
<th>Cantilever Dimension</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-polymer flow sensor in [38]</td>
<td>1.5</td>
<td>0.4</td>
<td>7.6</td>
</tr>
<tr>
<td>Sensor with improved sensitivity</td>
<td>3.5</td>
<td>0.6</td>
<td>7.6</td>
</tr>
</tbody>
</table>

2.1.3 Sensor Fabrication

The flow sensor used in the experiment is fabricated using the previously-reported flex-PCB-based process [38], which incorporates a laser-micromached Kapton® and a stencil-printed piezoresistive elastomer (carbon-black-loaded PDMS). A 125µm thick Kapton® film is laser machined with a CO₂ laser (Gravograph NewHermes) and laminated with a 7.6µm thick Kapton® film to form the base and device layers, respectively (Figure 32(a), (b)). A piezoresistor is then stencil-printed on the device Kapton® layer and cured at 130°C for 2 hours (Figure 32(c)). Interconnections between the piezoresistor and the external circuitry are achieved using silver epoxy (Figure 32(d)), followed by plasma-enhanced chemical vapor deposition (PECVD) of SiO₂ on the opposite side of the piezoresistor (Figure 32(e)). Finally, the out-of-plane microtuft is realized by a stress-gradient-induced curvature (where the stress is induced by a PECVD-deposited film of silicon dioxide on the device Kapton® at 150°C) and a subsequent
release by excimer laser (248nm, Lambda Physik) ablation of the in-plane cantilevers, nominally at room temperature (Figure 32(f)).

Figure 32. Fabrication process sequence of the all-polymer flow sensor [38]

Figure 33 shows the principle of the out-of-plane cantilever fabrication. PECVD silicon dioxide is deposited on the Kapton® cantilever at 150°C, as shown in Figure 33 (a). After the fabricated sensor cantilever is released at room temperature, the Kapton® film, with a larger thermal expansion coefficient (TEC) than silicon dioxide, will shrink more than the silicon dioxide. This manifests as a mismatch strain $\Delta \varepsilon$ (Figure 33 (b)), given by:

$$\Delta \varepsilon = (\alpha_k - \alpha_s) \Delta T,$$

(2.27)
where $\alpha_k$ and $\alpha_s$ are the thermal expansion coefficients of the Kapton® and silicon dioxide, respectively, and $\Delta T$ is the temperature difference. The values of these parameters are listed in Table 3.

**Table 3. Parameters for calculating the mismatch strain [63, 64]**

<table>
<thead>
<tr>
<th>$\alpha_k$ (°C⁻¹)</th>
<th>$\alpha_s$ (°C⁻¹)</th>
<th>$\Delta T$ (°C)</th>
<th>$\Delta \varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.5</td>
<td>130</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

This strain results in an internal strain in the cantilever beam and curls the cantilever (Figure 33 (c)). The curvature $k$ is related to the mismatch strain $\Delta \varepsilon$ by the following equation [65]:

$$k = \frac{6E_k E_s (t_k + t_s) t_s \Delta \varepsilon}{E_k t_k^4 + 4E_k E_s t_k^3 t_s + 6E_s E_s t_s^2 + 4E_k E_s t_s^2 t_s^2 + E_s^2 t_s^4},$$

(2.28)

where $E_k$ and $E_s$ are the Young’s modulus of Kapton® and silicon dioxide and $t_k$ and $t_s$ are the thickness of Kapton® and silicon dioxide. The relationship between curvature $k$ and the maximum cantilever deflection $D$ is given by:

$$D = \sqrt{2\left(\frac{1}{k}\right)^2 - 2\left(\frac{1}{k}\right)^2 \cos(lk) \sin\left(\frac{lk}{2}\right)},$$

(2.29)

![Figure 33. Principle of the TEC-mismatch-induced curvature](image-url)
Table 4. Parameters for calculating the TEC mismatch-induced curvature

<table>
<thead>
<tr>
<th>$E_k$ (GPa)</th>
<th>$E_s$ (GPa)</th>
<th>$t_s$ (µm)</th>
<th>$t_k$ (µm)</th>
<th>$k$ (mm$^{-1}$)</th>
<th>$D_{\text{theory}}$ (mm)</th>
<th>$D_{\text{measured}}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>72</td>
<td>0.6</td>
<td>7.6</td>
<td>436</td>
<td>2.19</td>
<td>2.7</td>
</tr>
</tbody>
</table>

During fabrication, the time-dependent behavior of TEC-mismatch-induced cantilever bending is observed: the cantilever bending curvature continues to increase (Figure 35). Will it takes too long for the cantilever to reach the steady state of the cantilever bending during sensor fabrication? To answer this question, the time dependent curvature of the cantilever is studied. The cause of this time dependent phenomenon is due to the viscoelasticity of the polymer material. In a viscoelastic material, stress will decrease as a function of time despite a constant strain [66]. The ratio between the time-dependent stress and the constant strain is called the relaxation modulus, given by [66]:

$$E(t) = \frac{\delta(t)}{\varepsilon_0}.$$  \hfill (2.30)

The relaxation modulus of a viscoelastic material can be modeled by Pory series expansion, given by:

$$E(t) = E_0\left[1 - \sum_{i=1}^{n} p_i (1 - e^{-t/\tau_i})\right].$$  \hfill (2.31)

In [67], with the tensile creep properties of the Kapton® film, the model of the relaxation modulus of Kapton® is given by:

$$\frac{E(t)}{E(0)} = 1 - (0.4706(1-e^{-t/0.3825}) + 0.07348(1-e^{-t/17.40}) + 0.0369(1-e^{-t/17.6})), \quad (2.32)$$

with minute as the unit of time. Replacing the Young’s modulus of Kapton® $E_k$ in (2.28) by the relaxation modulus $E(t)$ in Equation (2.32), we can derive the time-dependent curvature $k$. With the relationship between $k$ and maximum cantilever deflection $D$ given
in (2.29), we can determine the time-dependent cantilever deflection \( D \) as a result of the viscoelasticity of the Kapton\textsuperscript{®}. Figure 34 shows the theoretical results of maximum cantilever deflection \( D \) as a function of time with the viscoelasticity of Kapton\textsuperscript{®} modeled as shown in Equation (2.32). The results show that cantilever displacement will stabilize within 1000 minutes at around 2.253mm. This theoretical result agrees with the largest time constant of 117.6 minutes in the pony series in Equation (2.32). During fabrication, it takes approximately a day for the cantilever to reach its maximum deflection. The time for the cantilever to reach its steady state bending needs to be counted in the fabrication time. Both the analytical model and experimental observation show that this time is within a reasonable range, which will not result in an issue in fabrication.

Discrepancies between the modeling and the experimental results may come from cantilever property changes during and after fabrication because of plasma etching and humidity, the non-uniformity of silicon dioxide deposition, and the simplification of the model to a bi-layer structure without considering the elastomeric piezoresistor. To avoid complexity in modeling, we can introduce a correction factor \( c \) to correct the maximum cantilever deflection \( D \) resulting from the viscoelasticity of the material. The correction factor is defined by the measured cantilever deflection (stabilized, 2.7mm) divided by the simulation results (2.253mm), which yields \( c=1.2 \).
Figure 34. Simulation results of the maximum cantilever deflection vs. time
Figure 35. Changes in the cantilever curvature of the sensor as a function of time.

Figure 36 shows the fabricated all-polymer piezoresistive flow sensor. The cantilever-like microtuft is 3.5mm long, 0.6mm wide and 8.2μm thick. The elastomeric piezoresistor is 110μm wide, 1.9mm long, and 13μm thick. The measured resistance of the piezoresistor in its initial undeformed state is approximately 700kΩ.
2.1.4 Wind Tunnel Tests

A fabricated all-polymer flow sensor with the readout circuitry is tested in a bench top wind tunnel (ST 180 Scantek 2000), as shown in Figure 37. Assuming a typical air flow velocity of 15 m/s, the Reynolds number of the flow based on the wind tunnel geometry is approximately 200,000. At this Reynolds number, the flow over the airfoil results in a laminar boundary layer near the airfoil [68]. A thermal anemometer (Omega FMA-605-I) with a measurement range of 0-25m/s is used as a reference sensor for measuring the mean free stream wind velocity. Figure 38 shows the output resistance of the sensor as a wind velocity. Figure 39 shows both the simulated and the measured relative resistance change $\frac{\Delta R}{R_0}$ of the improved sensitivity flow sensor when the wind velocity varies between 0m/s and 15m/s. The simulation results show a higher sensitivity.
than the experimental results. The discrepancy between simulation and experimental results may come from many factors such as the cantilever stiffness change after oxide deposition, the simplification of a curled cantilever beam to a straight cantilever beam with an effective length, and the inaccuracy of applying Bernoulli’s equation for flow-pressure conversion. Introducing a correction factor can improve the accuracy of the model. Dividing the simulation results by a correction factor of 1.56 yields a better estimation of the sensor output, which is demonstrated in Figure 40. The relative resistance change $\frac{\Delta R}{R_0}$ of the sensor plotted against the square of the wind velocity $V^2$ shows a linear relationship in the sensor model in Equation (2.20). In Figure 41, $\frac{\Delta R}{R_0}$ increases linearly as a function of $V^2$ with a slope of approximately $4.3 \times 10^{-4}$ (m$^2$/s$^{-2}$), which is the value of the sensitivity coefficient $S$ in Equation (2.21). Compared to the all-polymer flow sensor in [38] with a sensitivity coefficient of approximately $1.4 \times 10^{-5}$ (m$^2$/s$^{-2}$), the improved sensitivity all-polymer flow sensor shows a sensitivity coefficient an order of magnitude higher because of the increase in length. Therefore, if both sensors experience the same baseline resistance drift, the wind velocity-referred sensor drift will be an order of magnitude lower in the improved sensitivity sensor. Figure 42 shows the sensor output resistance and the reference sensor output as the air flow is repetitively cycled between 0m/s and 14m/s. A greatly reduced wind velocity-referred sensor drift was observed.
Figure 37. (a) Schematic illustration of sensor testing and (b) wind tunnel experimental setup
Figure 38. Experimental results of the sensor output resistance vs. flow rate

Figure 39. Simulation (diamond) and measurement results (square) of the relative resistance change ($\Delta R/R$) of the sensor as a function of flow rate
Figure 40. Simulation (with a correction factor of 1.56, diamond) and measurement results (square) of the relative resistance change ($\Delta R/R$) of the sensor as a function of flow rate.

Figure 41. Simulation (with a correction factor of 1.56, diamond) and measurement results (square) of the relative resistance change ($\Delta R/R$) of the sensor as a function of flow rate squared.
2.1.5 Limitations of Single-Cantilever Design

It appears that further increasing the length of the cantilever could lead to higher sensitivity and thus smaller wind velocity-referred sensor drift. However, an increase in the length and a decrease in the width of the cantilever can lead to several problems. First, in most air flow sensor applications, especially in flight control applications involving UAVs, smaller air flow sensors are preferred because they minimize obstruction of the air flow without degrading the sensor performance. Second, as the
cantilever length increases, sensor array density will decrease, which results in a lower resolution for flow mapping using the sensor array along the cantilever direction. This issue can be solved by fabricating extra sensors and placing them between gaps on the substrate. However, this solution increases the complexity of both fabrication and packaging.

Another problem caused by changing the length and the width of the cantilever is that it becomes harder to control the bending angle of the out-of-plane cantilever, which might be due to non-uniform deposition of silicon dioxide. As the length increases, the process variation becomes large, which results in different bending angles (Figure 43). Furthermore, as the cantilever length increases, the stress gradient of the oxide will not only bend but also curl the cantilevers (Figure 43). The curling of the cantilever is time dependent (Figure 35), due to the viscoelasticity of the Kapton®. This time dependency exacerbates the control of bending in the cantilever. In an extreme case, the cantilever will roll, as shown in Figure 44.

Figure 43. Fabricated improved sensitivity all-polymer air flow sensors
2.2 A Dual-Cantilever All-Polymer Air Flow Sensor

If a constraint is placed on the length of the sensor, the parameters that could be adjusted are the thickness and the width of the cantilever. According to Equation (2.20), by reducing the thickness of the cantilever, the sensitivity could also increase. The thickness of the sensor depends on the thickness of the Kapton® substrate. In order to maximize sensitivity, the thinnest Kapton® sheet available (7.6µm) has been chosen. For a single cantilever flow sensor, the sensitivity does not depend on width of the cantilever, which is shown in Equation (2.20). Including the width \( w \) of the cantilever into Equation (2.20) yields

\[
\frac{\Delta R}{R_0} \approx (\pi_1 E' + 1 + 2\nu)\left(\frac{3l_{\text{eff}}^2}{Ew} \right)(p_{\text{wind}} \times w),
\]

(2.33)
which brings an intuitive explanation of the independence of the sensitivity to $w$: the sensitivity increase because of the decease of $w$ is cancelled by the decrease of the load intensity $p_{\text{wind}} \times w$. However, this explanation suggests if we can maintain the load intensity while reducing $w$, the sensitivity increases.

Figure 45 shows a dual-cantilever design for the all-polymer air flow sensor that reduces the cantilever width while maintaining the load intensity. The dual-cantilever design consists of two cantilevers (50μm×0.7mm), and a flapper (1.1mm×0.4mm) at the end. This design keeps a short length of the cantilever, reduces the width, and maintains the load intensity by the wide flapper. Furthermore, the dual-cantilever design allows self-alignment when the piezoresistor is patterned, which overcomes the patterning and alignment challenges when the cantilever width decreases. (A detailed discussion appears in the fabrication section.) The result is a simpler fabrication process than that described in [38].

As illustrated in Figure 26, the sensor consists of three layers: a flexible Kapton® substrate, an elastomeric piezoresistive layer (carbon black-loaded PDMS), and a thin silicon dioxide film deposited on the back of the Kapton® substrate. The latter results in a stress-gradient induced curvature of the microtuft. The sensing principle is the same as that of the previous sensor: air flow across the microtuft deforms the microtuft. The deformation, in turn, induces strain in the piezoresistor. The resistance of the piezoresistor, therefore, changes as a function of the strain induced by the applied wind velocity.
2.2.1 Device Analysis

For modeling the dual cantilever flow sensor, if we assume bending results from a force $F$ acting on the tip of the cantilever that is induced by the flapper, then the relationship between $F$ and the maximum displacement is as follows \cite{69}.

$$D_{\text{max}} = \left(\frac{l^3}{3EI}\right)F \quad (2.34)$$

The maximum strain occurs at the bottom surface of the cantilever beam, which is

$$\varepsilon_{\text{max}} = \frac{lt}{2EI} F. \quad (2.35)$$

Therefore,

$$\frac{\Delta R}{R} = (\pi_{11} E' + 1 + 2\nu) \varepsilon_{\text{max}} = (\pi_{11} E' + 1 + 2\nu) \frac{6l}{Ewt^2} F. \quad (2.36)$$

The relationship between the force and the wind velocity is still given by Bernoulli’s equation, but now the area over which the flow induces force is that of the flapper:

$$F = \frac{1}{4} \rho V^2 l' w' \quad (2.37)$$
where \( l' \) and \( w' \) are the length and width of the flapper. The reason \( \frac{1}{4} \) instead of \( \frac{1}{2} \) is used in Equation (2.37) is that there are two cantilever beams being strained by the flapper, so the flapper force in principle is divided between the two beams. Therefore,

\[
\frac{\Delta R}{R} = (\pi_{11}E' + 1 + 2\nu)\varepsilon_{\text{max}} = (\pi_{11}E' + 1 + 2\nu)\frac{3l'}{2Ewt^2}l'w' \rho V^2. \tag{2.38}
\]

Since the dual cantilever design is somewhat geometrically complex, the behavior is analyzed using ANSYS finite element software in addition to the analytical model above. Furthermore, the multiphysics capability of ANSYS is exploited in order to carry out the piezoresistive analysis, that is, transforming the mechanical strain to electrical resistance change. The finite element simulation includes:

1) Static analysis

The resistance change of the piezoresistor as a function of wind velocity will be analyzed. The sensor sensitivity will be calculated using simulation results and compared to the experimental results of the previous single cantilever flow sensor. In addition, the strain distribution on the cantilever under certain wind loads will be analyzed.

2) Modal analysis

The modal analysis is done to analyze the natural frequencies of the sensor, which is an important parameter for determining the sampling rate in the vibration amplitude measurement method.
Geometry modeling and loading

The device being modeled is a thin film composite consisting of three layers composed of silicon dioxide, Kapton® film, and a piezoresistive elastomer (carbon-black-loaded PDMS). The thickness of each layer is 0.65, 7.6, and 13 μm respectively, while the dimensions normal to the thickness are 1550 μm and 1800 μm. The resulting aspect ratio makes both solid and shell analysis appropriate. Appropriate element types include SHELL281, and SOLID186/226. The SOLID186/226 elements allow for the use of piezoresistive properties and require electric potential boundary conditions. Therefore, the geometric model is built with SOLID186/226 elements. The dimensions and material orientations relevant to the model are shown in Figure 46. Each material layer is divided into two elements in the thickness direction. All models utilized the vertical axis of symmetry that the loading, material, and geometry possess, enabling finer mesh densities and more rapid analysis.
The nodes, which will be rigidly fixed, are located at $y=0$ in the model, and rigid supports are illustrated on the solid model in Figure 47. One plane of symmetry exists in the device, therefore $x$-directional symmetry was applied accordingly, as shown by the supports with rollers in Figure 47, generating a condition of $U_x=0$, where $U_x$ is the displacement along $x$ direction, for all nodes at this boundary.

Figure 46. Overview of sensor geometry with relevant sections, layer orientation, and dimensions
Figure 47. Solid model and mesh with mechanical boundary conditions applied

In addition to mechanical boundary conditions, it was necessary to also apply electrical boundary conditions. The electric potential along the plane of symmetry within the piezoresistor was set to 0.5 V while the base of the piezoresistor was set to 0 V. An illustration of these boundary conditions can be seen in Figure 48.
Figure 48. Solid model and mesh with electrical boundary conditions applied.

Loading Conditions

Normal operating loads of the device are produced by laminar flow of air around the UAV airfoils. Since the focus of this study is on piezoresistive response and material behavior, two approximations of the wind load are considered.

The first approximation is to apply a constant pressure load distributed evenly over the surface of the device. It is then decided that the equivalent force of the wind be equally distributed among the surface nodes of the device. The formulation of how the load was applied follows. The pressure due to the wind was determined to be:

$$P = \frac{1}{2} \rho_{\text{air}} V^2$$

where $P$ is the applied pressure under wind loading of density $\rho_{\text{air}}$ and flow velocity $V$. The total force applied can then be calculated by multiplying by the area, $A$,
\[ F = PA = \frac{1}{2} \rho V^2 A \]  

(2.40)

where \( F \) is the total force applied to the device. The force \( F \) was divided by the total number of nodes and applies to the loads. An illustration of the applied loading can be found in Figure 49.

Figure 49. Illustration of wind loading conditions

Material Modeling

All materials modeled in this study were treated as homogeneous and isotropic in both mechanical and piezoresistive behaviors. All materials were first modeled using fundamental properties such as density (\( \rho \)), modulus of elasticity (\( E \)), and Poisson's ratio (\( \nu \)). The carbon-loaded PDMS was also modeled with a piezoresistive sensitivity to relate strains to generated resistance. These are the fundamental properties to conduct the static and modal mechanical analyses as well as producing a resistance response under static loading conditions. The mechanical material properties used for this set of analyses is
shown in Table 5 [63, 64, 70, 71]. The piezoresistive sensitivity used for the carbon black loaded PDMS is shown in Table 6 [38].

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic Modulus (GPa)</th>
<th>Poisson’s Ratio</th>
<th>Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>72</td>
<td>0.17</td>
<td>2650</td>
</tr>
<tr>
<td>Kapton*</td>
<td>2.5</td>
<td>0.34</td>
<td>1420</td>
</tr>
<tr>
<td>PDMS</td>
<td>0.0019</td>
<td>0.49</td>
<td>1120</td>
</tr>
</tbody>
</table>

Table 5. Linear-elasticity and other fundamental material properties

<table>
<thead>
<tr>
<th>Gauge factor</th>
<th>Piezoresistive sensitivity (Pa$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2</td>
<td>2.747×10$^{-6}$</td>
</tr>
</tbody>
</table>

Table 6. Piezoresistive property of the carbon black loaded PDMS for electrical analysis

Static analysis

In static analysis, the resistance change of the piezoresistor at specified wind velocities has been analyzed. Table 7 shows the analysis types and element types used in this simulation.

Table 7. Analysis types and element types

<table>
<thead>
<tr>
<th>Analysis type</th>
<th>Static, nonlinear geometry, linear-elastic analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Piezoresistor, Kapton®, SiO$_2$</td>
</tr>
<tr>
<td>Element type</td>
<td>SOLID226, SOLID186, SOLID186</td>
</tr>
</tbody>
</table>

In the multiphysics analysis, only half of the Wheatstone bridge is considered due to symmetry. In this ‘half-Wheatstone’ geometry, one resistive element varies due to the wind-loading-induced stress on the piezoresistive material comprising the element (Figure 50). The purple volume is modeled as a constant resistor. After applying the boundary condition and the wind load, ANSYS runs the simulation and extracts the voltage values at the interface of the constant resistor. The piezoresistor, located on top of
the purple volume, changes its resistance when the wind load varies. The change of the resistance results in a change in $V_0$, with which $\Delta R/R_0$ can be calculated. In the simulation, different flow rates are applied and the sensor resistance variation is derived from $V_0$.

![Figure 50. A half-Wheatstone bridge with one constant element and one variable piezoresistive element for sensor resistance simulation](image)

Figure 50 shows the simulation results of the dual-cantilever flow sensor. Both the relative resistance change as a function of flow rate and flow rate squared are plotted. With ANSYS simulation, the sensor demonstrates a sensitivity coefficient of $7.2 \times 10^{-4}$ (m$^2$/s$^2$). The sensitivity coefficient with theoretical modeling is slightly lower, because the flow pressure on the thin dual cantilevers has not been taken into account. Table 8 compares the geometries and sensitivity coefficient $S$ between the single (measured) and dual-cantilever sensors (simulated). The dual-cantilever design demonstrates a 167% increase in the sensitivity coefficient. This result shows that the dual-cantilever sensor performs with higher sensitivity even with a shorter cantilever length. The simulation results of the strain distribution along the y-axis (Figure 52) shows that the maximum
strain is located at the bottom of the cantilever, which is consistent with the theoretical results.

![Graph showing ANSYS simulation and theoretical results](image)

Figure 51. Simulation results of the relative resistance change of the sensor as a function of flow rate (left) and flow rate squared

<table>
<thead>
<tr>
<th>Geom.</th>
<th>Single cantilever</th>
<th>Dual cantilevers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.5mm (l) × 0.6mm (w)</td>
<td>0.7mm (l) × 50μm (w) Flapper: 0.4mm (l) × 1.1mm (w)</td>
</tr>
<tr>
<td>$S$</td>
<td>$4.3 \times 10^{-4}$</td>
<td>$7.2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 8. Comparison of the geometries and sensitivity coefficient between the single and dual cantilever sensors
Modal analysis

Modal analysis was carried out in order to find out the sensor resonant frequency. Shell elements were used instead of solid elements to save computational time. The simulated sensor natural frequency is 243.61Hz.

Table 9. Analysis types and element types

<table>
<thead>
<tr>
<th>Analysis type</th>
<th>Material</th>
<th>Element type</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modal analysis</td>
<td>Piezoresistor</td>
<td>SHELL281</td>
<td>243.61Hz</td>
</tr>
<tr>
<td></td>
<td>Kapton®</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SiO₂</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2.2 Device Fabrication and Characterization

The fabrication process shown in Figure 53 (left) results in simultaneous fabrication of multiple array elements using the laser micromachining process, as well as a reduction of process complexity through elimination of several previous processing steps in the fabrication process of the single-cantilever all-polymer flow sensor. The sensor is fabricated directly on a 7.6 μm-thick Kapton® film. The film is patterned using an LPX2000 series excimer laser (Lambda Physik) to form an in-plane cantilever (Figure 53 (a)). Table 10 lists the parameters of the excimer laser during micromachining of the Kapton® substrate.
A carbon-black-loaded conductive composite elastomer that displays high piezoresistivity is then prepared [38]. The conductive elastomer is carbon-black-loaded PDMS, which is a two-part mixture with a very high viscosity (7,000 Pa-sec). To prepare the piezoresistor, equal volumes of Part A and B are placed on a glass slide and mixed with a razor blade. Then the elastomer is coated over the cantilever surface using an inking process through an aligned stencil. Removal of the stencil results in an all-polymer microcilia array (Figure 53 (b)).

The inking process is described in Figure 54. A bench-top lamination tool distributes pressure evenly on the three layers illustrated in Figure 55. The bottom layer (Figure 55 (left)) is the laser-patterned 7.6 µm-thick Kapton® substrate. The middle layer is the inking mask made out of the 7.6 µm-thick Kapton® film. The top layer is, again, the same Kapton® film, with the piezoresistive elastomer spread with a blade. With pressure around 200 psi and duration of 10 seconds, a thin piezoresistive elastomer (around 16 µm) is printed on the Kapton® substrate evenly. The inking mask is micromachined with a CO2 laser (Gravo-graph Newhermes LS500XL series). One of the advantages of a CO2 laser over the excimer laser is speed: the maximum cutting speed of the CO2 laser reaches 200mm/s. However, the precision of a CO2 laser is low because of a large spot size around 160µ. During the inking process, no special alignment tools such as a jig described in [38] are necessary because of the self-aligned nature of the dual-cantilever design.

---

### Table 10. Parameters of the excimer laser

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Length (ns)</td>
<td>20</td>
</tr>
<tr>
<td>Pulse Frequency (Hz)</td>
<td>90</td>
</tr>
<tr>
<td>Pulse Energy (mJ)</td>
<td>200</td>
</tr>
<tr>
<td>Demag</td>
<td>10</td>
</tr>
<tr>
<td>Bursts</td>
<td>30</td>
</tr>
<tr>
<td>Spot size (µm)</td>
<td>30</td>
</tr>
</tbody>
</table>
Figure 54. Inking process for the printing of elastomeric piezoresistor

Figure 55. Layers in the inking process

Figure 56 shows the principle of the self-alignment. Since the cantilever is designed to be covered with the piezoresistive elastomer over its entire surface, as long as the cantilever is fully exposed to the elastomer through the mask, the alignment error between the inking mask and sensor structure will not have any effect on the piezoresistive material deposition. On the left side of Figure 56, even though there is an alignment error along the x-axis, the elastomer still covers the entire sensor structure. In other words, the alignment error will not affect piezoresistor patterning. This statement is
still true if the alignment error is along the positive $y$-axis. However, if the alignment error is along the negative $y$-axis, the error may result in a short in the piezoresistor as illustrated in Figure 57 (left). A slight modification of the sensor design resolves this issue (Figure 57(right)).

![Figure 56. Self-alignment principle](image)

![Figure 57. Design modification for avoiding short in piezoresistor](image)

After the inking process, the Kapton® substrate with piezoresistive elastomer patterned is placed in an oven for curing. The curing temperature is around 130°C and curing time lasts 2 hours. Copper electrodes (3000Å) are then e-beam evaporated at a rate
of 3Å/sec (Figure 53 (c)). A shadow mask is used for patterning the metal. The shadow mask is fabricated using the CO$_2$ laser on a 125µm thick Kapton$^\text{®}$ film. By covering the substrate and exposing the area to be metalized, the Kapton$^\text{®}$ shadow mask will transfer its pattern onto the sensor substrate.

Finally, the out-of-plane cantilever is realized by a stress-gradient-induced curvature using PECVD of silicon dioxide film deposited on the electrode areas of the device layer (Figure 53 (d)). The fabrication recipe is shown in Table 11. With 16mins deposition time, a 0.65µm thick oxide is deposited on the sensor backside.

In previous chapters, an issue of sensor structure curling was described. This issue is solved by limiting the oxide deposition within the area shown in Figure 58 with a shadow mask. The sensor shows a bending around 90 degrees without the two cantilever beams and the flapper being curled. However, the time dependent bending of the sensor structure still happens because of the viscoelasticity of the Kapton$^\text{®}$ film.

**Table 11. Fabrication recipe for silicon dioxide deposition**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Flow (sccm)</th>
<th>Pressure (mTorr)</th>
<th>Power (W)</th>
<th>Deposition rate (Å/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiH$_4$</td>
<td>400</td>
<td>900</td>
<td>25</td>
<td>400</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>900</td>
<td>900</td>
<td>25</td>
<td>400</td>
</tr>
</tbody>
</table>
Figure 58. Oxide deposition using a shadow mask

Figure 59 shows a fabricated sensor array mounted on a curved surface with a zoomed-in picture demonstrating the sensor structure, which comprises a Kapton® substrate (yellow), an out-of-plane Kapton® microcilia coated with a carbon-black-loaded PDMS elastomeric piezoresistor (black), and copper metal interconnections (shining brown).

Figure 59. Fabricated dual-cantilever all-polymer flow sensor array
The fabricated sensor is tested in the wind tunnel setup described in Figure 37. Figure 60 shows the measured sensor resistance as a function of flow rate. Figure 61( left) compares the measurement results (diamond) and the ANSYS simulation results (square) of the relative resistance change ($\Delta R/R$) of the sensor as a function of flow rate. The experimental results and the simulations results fit well, which demonstrates a higher accuracy of the model in the ANSYS simulation than the simplified model of the single-cantilever sensor. Figure 61(right) replots Figure 61(left) with flow rate squared in the x-axis, which allow us to extract the sensitivity coefficient $S$. The experimental results show that the sensitivity coefficient $S$ is $7.6\times10^{-4}$ (m$^2$/s$^{-2}$), 177% times higher than that of the single cantilever flow sensor with a cantilever length of 3.5mm.

![Figure 60. Measured sensor resistance as a function of flow rate](image-url)
Figure 61. Simulation (square) and measurement results (diamond) of the relative resistance change ($\Delta R/R$) of the sensor as a function of flow rate (left)/flow rate squared (right)

Table 12 shows the statistics of the baseline resistance $R_o$ and the sensitivity coefficient $S$ of 6 fabricated sensors. These sensors show a large standard deviation of the sensor baseline resistance $R_o$, which is because the printing of the elastomeric material is not well controlled. Figure 62 shows the measurement results of the relative resistance change ($\Delta R/R$) of 6 fabricated sensors as a function of flow rate squared. The scattered data points show that the process control of the polymer-based flow sensor is challenging. To make identical sensors, improvements in process and/or sensor design are required.

Table 12. Baseline resistances and sensitivity coefficient $S$ of 6 fabricated sensors

<table>
<thead>
<tr>
<th>Sensor number</th>
<th>$R_o$ (kOhm)</th>
<th>$S \times 10^{-4}$ (m$^2$/s$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>491.2</td>
<td>7.16</td>
</tr>
<tr>
<td>2</td>
<td>356.8</td>
<td>8.15</td>
</tr>
<tr>
<td>3</td>
<td>801.4</td>
<td>8.04</td>
</tr>
<tr>
<td>4</td>
<td>728.2</td>
<td>7.77</td>
</tr>
<tr>
<td>5</td>
<td>851.0</td>
<td>7.12</td>
</tr>
<tr>
<td>6</td>
<td>602.6</td>
<td>8.31</td>
</tr>
<tr>
<td>Average</td>
<td>638.5</td>
<td>7.76</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>190.8</td>
<td>0.51</td>
</tr>
</tbody>
</table>
2.2.3 A Large All-Polymer Air Flow Sensor Array

With laser micromachining, an eight-sensor array has been successfully fabricated. However, if the array size is to be expanded, the time consumption of laser micromachining raises an issue. Laser cutting is a serial process, and can be time consuming when a large number of sensors are needed. Take the previously fabricated eight-sensor array, for example. The laser micromachining of the sensor structure takes around 1 hour 15 minutes. If an 8×8 sensor array is to be fabricated, the fabrication time will be 10 hours. Therefore, to achieve a large sensor array, a parallel fabrication process for fabricating sensor structures is needed to replace laser micromachining.

RIE was reported for the micromachining of polyimide films [72]. The reported etch rate of 1-4 µm/s makes this technology appealing compared to the laser micromachining process for large array fabrication. The time consumption for making an $n \times n$ array will be independent of the array size, assuming the chamber is large enough to place the substrate, but reliant on the substrate thickness and the etch rate. The thickness of the all-polymer flow sensor is 7.6µm. With an etch rate around 1µm/min, the
fabrication time consumption will be 7.6mins. The RIE process is developed in the Plasma-Therm RIE machine (Plasma-Therm Inc.). Table 13 shows the fabrication recipe for Kapton® etching. Figure 63 presents the fabrication results of a dual-cantilever structure on a Kapton® substrate with RIE.

Table 13. Fabrication recipe for Kapton® dry etching

<table>
<thead>
<tr>
<th>Gas</th>
<th>Flow (sccm)</th>
<th>Pressure (mTorr)</th>
<th>Power (W)</th>
<th>Etch rate (µm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>1</td>
</tr>
<tr>
<td>SF₆</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 63. Fabrication results of a dual-cantilever structure on a Kapton® substrate with RIE

To selectively etch the Kapton® substrate for sensor structure release, a mask on the substrate is needed. Al is proven to be a good mask material for Kapton® etching in RIE. The Al mask is patterned though a lift-off process, which is described in detail in Appendix A. During the lift-off process, a descum with O₂ plasma is critical prior to the Al deposition. The tool used for this descum process is the same tool used for Kapton® etching, with a recipe listed in Table 14. Figure 64 shows a comparison between masks
on the substrate, after lift-off, with and without the O₂ plasma descum, which removes photoresist residues and cleans the substrate.

Table 14. Fabrication recipe for the descum process

<table>
<thead>
<tr>
<th>Gas</th>
<th>Flow (sccm)</th>
<th>Pressure (mTorr)</th>
<th>Power (W)</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>50</td>
<td>200</td>
<td>200</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 64. Al masks on a Kapton® substrate with descum (left) and without descum (right) before Al deposition

Once the in-plane cantilever structures are released by RIE, the rest of the fabrication processes are identical to the fabrication process of the laser-micromachined dual-cantilever sensor. Figure 65 shows the fabricated large sensor array and Figure 66 shows the fabricated array mounted on a Flex-PCB with a multiplexer for flow mapping.
2.2.4 Interfacing Circuit

In the previous section, large sensor arrays with high sensitivity are successfully fabricated. To use this sensor array for UAV control application such as flow mapping, sensor interfacing circuit is necessary. A block diagram of the sensor readout circuit for the measurement of the all-polymer flow sensor is shown in Figure 67. The piezoresistor in the flow sensor is connected to a single-element-varying, voltage-driven Wheatstone bridge, which is composed of three non-variable resistors and the piezoresistive sensor as the varying element. The output of the bridge is fed to an instrumentation amplifier as a
gain stage. When there is a resistance variation $\Delta R$ in the piezoresistor with an initial resistance of $R$, the output of the instrumentation amplifier is given by:

$$
V_o = \frac{1}{2} \left( \frac{\Delta R}{2R_0 + \Delta R} \right) V_s \approx \frac{1}{4} V_s \left( \frac{\Delta R}{R} \right) G,
$$

(2.41)

where $V_s$ is the supply voltage of the bridge and $G$ is the gain of the amplifier. In order to convert the resistive output to a voltage output, a microcontroller or a Labview setup is used for data acquisition and signal processing.

The sensor interface circuitry introduces noise into the whole system. The sources of noise include thermal noise of the resistors and the piezoresistor in the Wheatstone bridge; thermal, shot, and 1/f noise from transistors in the amplifier, multiplexer and microcontroller; and the quantization noise during the analog to digital conversion. A low noise sensor interface circuit will result in a sensor system with high signal to noise ratio.

![Figure 67. Schematic of the sensor array read-out circuitry](image)
2.2.5 Large Sensor Array Measurements and Applications

A fabricated all-polymer flow sensor array with the readout circuitry described in Figure 67 is tested in the bench top wind tunnel. In order to demonstrate the array mapping functionality, a multiplexed 4×4 cilia sensor array was placed on a flat plate in the bench-scale wind tunnel. Nominally uniform flow of varying velocity was passed over the sensor array. Figure 68 shows flow mapping over a 40×40mm² area using the sensor array with the multiplexed array read-out circuitry. Measurement results demonstrate the flow mapping capability of the array with the multiplexed array read-out at different flow rates.

![Normalized sensor resistance vs. flow rate](image)

**Figure 68. Flow mapping over a 40×40mm² area using 16 sensors with array read-out circuitry**

![Flow tunnel setup: airfoil attached with actuators and a flow sensor array](image)

**Figure 69. Wind tunnel setup: airfoil attached with actuators and a flow sensor array.**
The flow sensor/sensor array has also been tested on airfoils to verify its capability for flow sensing. The measurement setup is demonstrated in Figure 69, that is, an airfoil with both sensors and actuators mounted on its surfaces.

Figure 70. Measurement Principle

The measurement principle is shown in Figure 70. Assuming a typical air flow velocity of 30 m/s, if the sensor is placed at x=10 cm away from the leading edge, the Reynolds number of the flow based on sensor position from the leading edge is approximately 200,000. At this Reynolds number, the flow over the airfoil results in a laminar boundary layer [68], with a boundary layer thickness given by the Blasius equation and estimated as:

\[
\frac{d}{x} = \frac{5}{\sqrt{\text{Re}}}
\]

where \(d\) is the boundary layer thickness. From this equation, the boundary layer thickness exceeds 1mm, assuming the substrate is a flat plate. With a total length of approximately 1mm, the sensor is within the estimated boundary layer thickness. When the airfoil is at a low angle of attack, air flow attaches to the airfoil with a small boundary layer thickness.
resulting in a large flow rate across the sensor structure; therefore, sensors exhibit a large bending as well as a large vibration amplitude, which translates to a large sensor output. When the angle of attack increases, the boundary layer thickness on the airfoil surface increases which results in a decrease in flow velocity around sensors mounted on the airfoil [73]. As a result, the sensor output decreases until flow separates. The actuators are able to reattach the flow by providing flow with extra momentum. Once the flow is reattached, the boundary layer thickness decreases again, which results in an increase in flow velocity across sensors. Once again, the sensor output will increase.

Figure 71. Sensor output vs. angle of attack

The sensor output as a function of the angle of attack is shown in Figure 71. We can observe that as angle of attach increases, sensor output decreases. Furthermore,
according to the lift force measured by an external force sensor, stall occurs at an angle of attack of 18~20 degrees, which can be detected by the sensor.

Figure 72. Sensor output vs. actuator status (ON/OFF)

Figure 72 demonstrates the sensor output as a function of actuator status, which shows that as actuators are ON, sensor output increases indicating that the flow rate across the sensor increases.

A sensor array with interfacing circuitry is also placed on a small-scale airfoil, which is shown in Figure 73, to map the flow.
Figure 74. Flow mapping of a 40×40mm² area with 16 sensors vs. angle of attack.

Figure 74 shows the sensor array output as the angle of attack changes. The sensor output is considerably smaller at an angle of attack of 18 degrees compared to the sensor output when the angle of attack is 4 degrees or 12 degrees, while lift coefficient ($C_L$) measured by an external force sensor (Figure 75) shows that stall occurs at approximately 18 degree angle of attack.

Figure 75. Lift coefficient vs. angle of attack.
In order to reattach the flow to increase the lift force, the actuators mounted on the airfoil are turned ON. A dramatic increase in sensor outputs shows that the flow has been successfully reattached, which is confirmed by lift sensor data as well.

2.3 Active Wireless Sensor System

The focus of this section is an active wireless sensor system; which is demonstrated in Figure 76. Compared to the microcontroller-based sensor interfacing circuit described in Figure 67, a 4-turn coil with a diameter around 2cm (0.5µH) is connected with an I/O pin (P3.0, rail-to-rail) of the MSP430 microcontroller (msp430FG4618, Texas Instruments) with a 3.3V single supply for emitting the frequency-modulated signal. A 1k resistor is used for limiting the current passing the inductor. A 6-turn coil with a diameter of around 5cm (3µH) is connected with a spectrum analyzer (HP 8591E) for signal detection. Figure 77 shows the wireless sensing setup for the all-polymer airflow sensor. The wind tunnel is the same as the one described in Figure 37.

![Figure 76. A block diagram of the active wireless system](image)
An algorithm described in Figure 78 is implemented in the microcontroller (see Appendix B). The principle of the algorithm shown in Figure 78 is to convert the sampled sensor voltage value into a delay $D$, which controls the frequency of the microcontroller output. In the experiment, the delay $D$ is set to be 20% of the voltage output. When flow rate increases, the microcontroller detects a large sensor output, which results in a large delay. The larger delay, in turn, reduces the microcontroller output frequency, which is then detected by the spectrum analyzer.
To understand the relationship between delay $D$ and the output frequency, signal and noise power in the receiver, the microcontroller is programmed to vary the delay $D$, and the spectrum analyzer measures frequency variation wirelessly. The distance between the coils is 5cm. The noise level is around 108dbm. The relationship between delay $D$ and frequency is

$$f \propto \frac{1}{D},$$

which is demonstrated in Figure 79. The induced voltage in a coil is proportional to the field frequency.

$$V \propto f.$$  \hfill (2.44)

Then we have the following relationship

$$P_{\text{dbm}} \propto 40\log f.$$  \hfill (2.45)
This relationship is also shown in Figure 80. Figure 81 shows the wirelessly measured frequency as a function of flow rates.

Figure 79. Output frequency as a function of delay $D$

Figure 80 Detected signal power as a function of frequency
Figure 81. Wirelessly detected frequency as a function of flow rates
CHAPTER 3

POLYMER-BASED METAL PIEZORESISTIVE FLOW SENSOR

In the previous chapter, a dual-cantilever sensor design results in a higher sensitivity, therefore, a lower flow-velocity-referred drift. In this chapter, another direction will be taken to resolve the drift issue. Since the root cause of the drift in all-polymer sensors is the instability of the polymer material, a more stable sensing material, Pt, will be used as the sensing element. Furthermore, by introducing Pt in the sensor fabrication, the fabrication process is tremendously simplified.

3.1 Device Design and Sensing Principle

If we replace the elastomeric piezoresistor with other piezoresistive materials in the all-polymer flow sensor, the material has to be flexible, sensitive (high gauge factor), and stable. Among different materials, silicon is a great choice in terms of stability and sensitivity; however silicon is rigid and brittle. Metal piezoresistive strain gauges are widely used in stress/strain detection. In MEMS, thin film metals are often patterned as piezoresistors. These metal piezoresistors are flexible and have a moderate gauge factor. Among the metal piezoresistors, Pt has a gauge factor around 6 and, as a noble metal, it is resistive to corrosion and oxidation. Therefore, the Pt piezoresistor will replace the elastomeric piezoresistor in the new sensor.

As illustrated in Figure 82, the sensor comprises two layers: a flexible Kapton® substrate and a Pt piezoresistive layer, which is sputtered on the Kapton® substrate as a sensing material. The sensing principle is the same as that of the all-polymer flow sensor: when air flows across the microtuft, the microtuft deforms. The deformation, in turn,
induces strain in the Pt piezoresistor. The resistance of the piezoresistor therefore changes as a function of the strain induced by the air flow.

![Figure 82. Front view and side view of the metal piezoresistive air flow sensor as well as the sensing principle](image)

**3.2 Device Fabrication**

The block diagram in Figure 83 demonstrates how the process is simplified by introducing Pt as a sensing element. First, the main fabrication steps of the polymer flow sensor are shown on the left side of the figure. Step 1 is the deposition of Al mask on the Kapton® substrate. Step 2 is the RIE for Kapton® etching. After the RIE, the area without Al will be etched and an in-plane cantilever is formed. The Al mask will be etched after the RIE. Step 3 is the piezoresistor deposition and step 4 is the oxide deposition resulting in an out-of-plane cantilever.

In the polymer-based metal piezoresistive flow sensor, Pt will replace the elastomeric piezoresistor. The piezoresistive material covers the entire cantilever with the
dual-cantilever design. Since Pt is a noble metal, it can be used as the RIE mask as well. Therefore, step 1 (mask deposition) and step 3 (piezoresistor deposition) can be combined. Furthermore, because of the TEC mismatch between Pt and Kapton® film and a deposition temperature higher than room temperature, the Pt layer will introduce a stress on the microtuft and therefore form an out-of-plan structure. For this reason, step 4 (back side oxide deposition) can also be eliminated.

Figure 83. Fabrication process simplification from (a) all polymer flow sensor to (b) polymer-based metal piezoresistive flow sensor
The simplified two-step fabrication process is described in Figure 84. First the Pt piezoresistors are sputtered and patterned on a 7.6μm thick Kapton® sheet using a lift-off process (Figure 84 (a)). In the lift-off process, 1000 Å Pt is sputtered in a unifilm sputter (PVD300, Unifilm Technology) with a rate of 100 Å/min. After the metallization, the Kapton® substrate is immersed in acetone and a swab is used to gently wipe the substrate to help the lift-off. Figure 85 shows the Pt patterns on the substrate after the lift-off process. The Pt thin film bends with the Kapton® substrate, showing that the Pt thin film satisfies the flexibility requirement. In the second step, the substrate undergoes RIE with a Kapton® shadow mask (Figure 86), which is laser-micromachined (the CO2 laser described in Chapter 2) (Figure 84(b)). After the RIE, an out-of-plane microtuft is formed by thermally-induced stress gradients and the sensor fabrication is completed. Figure 87 shows the fabricated flow sensors, which consist of a microtuft comprising two cantilevers with 0.7mm in length and 50μm in width and a 1.1mm wide and 0.4mm long flapper at the end.
Figure 85. Sensor array after fabrication step one

Figure 86. Kapton® mask for releasing the microtufts
3.3 Device Characterization

A fabricated sensor is tested in the bench-top wind tunnel (ST 180 Scanteck 2000). The thermal anemometer (Omega FMA-605-I) is used as a reference sensor for measuring the mean free stream wind velocity. The resistance changes of the sensor are measured by the digital multimeter (Keithley). The measured sensor resistance as a function of wind is shown in Figure 88. As wind increases, the sensor resistance decreases as a result of compressive strain in the Pt piezoresistor of the sensor. The sensor output saturates at around 6m/s. This saturation is probably due to the increased base area (two rectangular pieces underneath each narrow cantilever beams) of the device, which is designed to increase the sensor’s bending angle. The saturation of the sensor output is also observed in a transient response of the sensor shown in Figure 89. Figure 90 shows the simulation (square) and measurement results (diamond) of the relative resistance change ($\Delta R/R$) of the sensor as a function of flow rate (left)/flow rate squared (right). The experimental results show a higher sensitivity coefficient than the ANSYS
simulation results. A possible cause of this discrepancy is the mechanical property change of the cantilever beams after Pt sputtering and RIE.

Figure 88. Sensor output resistance as a function of the wind velocity

Figure 89. Output of the polymer-based metal piezoresistive flow sensor: reference wind velocity (upper) and the measured sensor response (lower)
Experimental results of 5 polymer-based Pt piezoresistive flow sensors are plotted in Figure 91. The figure shows the relative resistance change $\Delta R/R$ as a function of flow rate squared. The experimental results show an average $S$ of $1.29 \times 10^{-4} (m^2/s^2)$, which is much smaller than the results of the dual-cantilever all-polymer flow sensors ($S=7.76 \times 10^{-4} (m^2/s^2)$). However, the sensor results show a better consistency because the fabrication of the Pt piezoresistor is better controlled than that of the elastomeric piezoresistor. Table 15 shows the initial resistance $R_0$ in the piezoresistor and the sensitivity coefficient $S$ of the sensor, which shows a standard deviation of 0.0492 Ohm in the baseline resistances and 0.126$(m^2/s^2)$ in the sensor sensitivity, much smaller than those of the all-polymer flow sensor as a result of better process control during the piezoresistor deposition. A sensor baseline resistance drift in 6 hours is also measured to calculate the sensor wind velocity-referred drift (Table 16). Despite the sensor’s low sensitivity, the sensor demonstrates a low wind-velocity-referred sensor drift because of its low resistance drift.

In the end of this chapter, a summary of the piezoresistive bio-mimetic flow sensors with different is shown in Table 17. The three polymer-based flow sensors show a higher sensitivity than their silicon counterpart, which is because of the choice of sensor material, design, and geometry.
Figure 91. Measurement results of the relative resistance change ($\Delta R/R$) of 5 sensors as a function of flow rate squared

Table 15. Baseline resistance and sensitivity coefficient $S$ of 5 fabricated Pt piezoresistive flow sensors

<table>
<thead>
<tr>
<th>Sensor number</th>
<th>$R_o$ (Ohm)</th>
<th>$S$ ($\times10^{-4}$m$^2$/s$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62.614</td>
<td>1.41</td>
</tr>
<tr>
<td>2</td>
<td>62.618</td>
<td>1.41</td>
</tr>
<tr>
<td>3</td>
<td>62.547</td>
<td>1.26</td>
</tr>
<tr>
<td>4</td>
<td>62.680</td>
<td>1.25</td>
</tr>
<tr>
<td>5</td>
<td>62.647</td>
<td>1.11</td>
</tr>
<tr>
<td>Average</td>
<td>62.621</td>
<td>1.29</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.0492</td>
<td>0.126</td>
</tr>
</tbody>
</table>

Table 16. Baseline resistance drift of the sensor and its wind velocity-referred drift

<table>
<thead>
<tr>
<th>Initial resistance ($\Omega$)</th>
<th>Resistance after 6hrs ($\Omega$)</th>
<th>Resistance drift (%)</th>
<th>Sensor sensitivity ($%/(m/s)$)</th>
<th>Sensor drift (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>61.0197</td>
<td>61.0536</td>
<td>0.056</td>
<td>0.062</td>
<td>0.9m/s</td>
</tr>
</tbody>
</table>
Table 17. Summary of piezoresistive bio-mimetic flow sensors with different designs and geometry (the sensitivity coefficients are calculated from given references)

<table>
<thead>
<tr>
<th></th>
<th>Sensing material</th>
<th>Cantilever material</th>
<th>Cantilever geometry (µm)</th>
<th>Sensitivity coefficient ($\times 10^{-4}$ m$^{-2}$/s$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Silicon-based flow sensor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fan et. al. [31]</strong></td>
<td>Si (Boron Ion)</td>
<td>Metal/polymer–permalloy</td>
<td>820-1100 ×100-200 ×10</td>
<td>308 (in liquid flow, equivalent to 308× $\rho_{\text{air}}/\rho_{\text{liquid}}$ =0.4 in air flow)</td>
</tr>
<tr>
<td><strong>Chen et. al. [32]</strong></td>
<td>Si (Boron Ion)</td>
<td>SU-8</td>
<td>600 ×80</td>
<td>0.44</td>
</tr>
<tr>
<td><strong>Wang et. al. [27]</strong></td>
<td>Pt</td>
<td>Si$_3$N$_4$</td>
<td>4000 ×400-2000</td>
<td>0.79 ($W_{\text{beam}}$=1200 µm)</td>
</tr>
<tr>
<td><strong>Zhang et. al. [74]</strong></td>
<td>Si</td>
<td>SiO$_2$</td>
<td>100-400 ×20-40</td>
<td>438 (in liquid flow, equivalent to 0.57 in air flow)</td>
</tr>
<tr>
<td><strong>Polymer-based flow sensor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Aiyar et al. [38]</strong></td>
<td>Elastosil®</td>
<td>Kapton®</td>
<td>1500 ×400</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>This work:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improved sensitivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>single cantilever</td>
<td>Elastosil®</td>
<td>Kapton®</td>
<td>3500 ×600</td>
<td>4.3</td>
</tr>
<tr>
<td><strong>This work:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual-cantilever</td>
<td>Elastosil®</td>
<td>Kapton®</td>
<td>Dual cantilevers: 700 ×50 Flapper: 400×1100</td>
<td>7.6</td>
</tr>
<tr>
<td><strong>This work:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal piezoresistive</td>
<td>Pt</td>
<td>Kapton®</td>
<td>Dual cantilevers: 700 ×50 Flapper: 400×1100</td>
<td>1.25</td>
</tr>
</tbody>
</table>
CHAPTER 4

DRIFT REDUCTION IN AN ALL POLYMER AIR FLOW SENSOR

In previous chapters, we saw that increasing sensitivity of the sensor or applying a sensing material with less drift reduced the sensor drift. These approaches can be summarized as “a better sensor”. In general, “a better sensor” translates to higher cost or higher fabrication/design complexity, and longer time for research and development.

In this chapter, an approach for drift reduction other than “a better sensor” will be discussed. The approach is called vibration amplitude measurement method, which measures flow rate by discriminating the amplitude of the flow-induced vibration (‘flutter’) of the flow sensor. The chapter starts with a review of the work in the flow-induced vibration of cantilever structures. Then the principle of the vibration measurement method and how this method reduces sensor drift will be explained. After the theoretical discussion, implementation of the measurement method and test results will show the drift reduction capability of the method.

4.1 Flow-Induced Vibration

Flow-induced vibration is everywhere. When wind passes a plant, branches and leaves will move back and forth; up and down; in other words, vibration happens. If it is a breeze, the vibration is often small and can only be observed if we take a close look at the plant. However, if it is a storm, the vibration becomes large and obvious. Poet William Wordsworth, in his famous poem “Daffodils”, describes the flow-induced vibration of “a host of Golden Daffodils” as “Fluttering and dancing in the breeze”. In
in fact, the “fluttering” effect is a term to describe the flow-induced vibration of a structure; an equivalent term is ‘galloping’ [62, 75, 76].

The flow sensor, or the cantilever structure, also vibrates. In the wind tunnel test, flow-induced vibration of the sensor structure is observed, which is also reflected by the sensor response. By closely observing the sensor output response, a fluctuating resistance is seen (Figure 19) [38]. Could we exploit this aerodynamic phenomenon and use the vibration as a way to measure flow rate? Before answering this question, two questions should be first investigated.

1. What kind of structure will vibrate in a flow?
2. Is the vibration amplitude proportional to flow rate?

The answer to the first question is that, if a structure has a noncircular cross-section, it is susceptible to flow-induced vibration [75]. Different geometry demonstrates different stability in flow. The cantilever, for instance, becomes more and more unstable as its length over width ratio increases [75]. In [77], the authors analyze the flow-induced vibration of a slender cantilever plate illustrated in Figure 92. The equation of motion of the cantilever plate is given by

\[ m \frac{\partial^2 y}{\partial t^2} + EI \frac{\partial^4 y}{\partial x^4} = w \Delta P = w(P_{nc} + P_\gamma), \tag{4.1} \]

where \( m \) is the mass per unit length of the cantilever, \( E \) is the Young’s modulus, \( I \) is the moment of inertia, \( w \) is the width of the plate, and \( \Delta P \) is the pressure difference between the top and bottom of the plate, which is decomposed to non-circulatory pressure (\( P_{nc} \)), governed by Bernoulli’s equation and circulatory pressure (\( P_\gamma \)) because of vortex shedding at the trailing edges [77]. The authors state that the structure starts fluttering at flow velocity above the critical flutter velocity \( (U_c) \), with the scaling law of \( U_c \) given by
$$U_c \sim \sqrt{\frac{Eh^3}{\rho_f L^2}},$$

(4.2)

where $E$ is the Young’s modulus of the plate, $h$ is the thickness, $L$ is the length, and $\rho_f$ is the density of the fluid [77]. With the geometry of the single cantilever flow sensor in Chapter 2, Equation (4.2) yields 5.3m/s, which is close to the experimental result of the $Uc$ around 5m/s.

Figure 92. A flapping plate studied in [77]

The answer to the second question is “Yes”; the vibration amplitude of the fluctuation is proportional to the wind velocity [76]. In [76], the flow-induced vibration of a square section cantilever beam (Figure 93) is both theoretically and experimentally studied.
The equations of the motion of the cantilever are given by

\[
\frac{m}{\ddot{w}} + c \frac{\dot{w}}{\dot{t}} + E I \frac{\dddot{w}}{\ddot{x}} = \frac{1}{2} \rho U^2 b C_z \left( \frac{1}{2} \frac{w}{U}, \frac{v}{U}, \alpha_0 \right)
\]

\[
\frac{m}{\ddot{v}} + c \frac{\dot{v}}{\dot{t}} + E I \frac{\dddot{v}}{\ddot{x}} = \frac{1}{2} \rho U^2 b C_y \left( \frac{1}{2} \frac{w}{U}, \frac{v}{U}, \alpha_0 \right),
\]

where \( m \) is the mass per unit length of the cantilever, \( c \) is the damping, \( E \) is the Young’s modulus, \( I \) is the moment of inertia, \( \rho \) is the density of the flow, \( b \) is the size of the square, \( C_z \) and \( C_y \) are the force coefficients [76]. The authors use Galerkin’s method to solve the equations and give the vibration amplitude of the beam by:

\[
\frac{1}{2} \left( \frac{1}{u} - Z_1 \right) / 1.761 Z_1^{1/2},
\]

with the minimum flow rate for the onset of the fluttering as:

\[
U = \frac{4cZ_1}{2\rho b}
\]
where $Z_1$ (positive) and $Z_3$ (negative) are the coefficients relating to the lift and drag coefficients of the structure [76]. As $\ddot{u}$ increases, $1/\ddot{u}$ becomes negligible. Equation (4.4) becomes:

$$\frac{\ddot{a}}{u} \approx \{[-Z_1]/1.761Z_3\}^{1/2} \approx (Z_1)/1.761|Z_3|^{1/2}. \quad (4.6)$$

Since $Z_1$ and $Z_3$ are constants dependent on the geometry of the structure, Equation (4.6) suggests that the ratio of amplitude to velocity is also a constant, or the amplitude of vibration is proportional to the flow velocity (above the threshold velocity). In [76], the proportionality between vibration amplitude and flow rate is shown not only theoretically but also experimentally.

In order to verify this phenomenon in the sensors in this research, the resistance change in the all-polymer flow sensor is empirically characterized with varying wind velocity. As shown in Figure 94, the amplitude of the vibration-induced resistance increases as the wind velocity increases. This confirms the validity of the proposed vibration amplitude measurement method.
Figure 94. Sensor output of the polymer-based flow sensor using direct resistance measurement with different wind velocities applied: wind velocity profile (upper) and sensor output (lower). Note that the vibration amplitude increases as the wind velocity increases.

4.2 Vibration Amplitude Measurement

Based on the observation in Figure 94, the sensor readout scheme of Figure 95 is proposed. As shown in Figure 95, the amplitude of changes in the vibration-induced resistance increases when the wind velocity becomes larger, independent of the absolute value of resistance. Therefore, the baseline drift can be reduced by filtering out low frequency signals from the sensor output, followed by signal processing for peak-to-peak amplitude calculation. It is assumed that baseline drift is slow compared to the time scale of the flow-induced sensor vibration.
In order to extract the peak-to-peak vibration amplitude of the sensor output and convert the resistive output to a voltage output, a microcontroller (MSP430F2012, Texas Instruments) with built-in 10-bit successive approximation (SAR) analog-to-digital converter (ADC) is used for data acquisition and signal processing. A block diagram of the sensor readout circuit for the vibration amplitude measurement of the all-polymer flow sensor is shown in Figure 96. The piezoresistor in the flow sensor is connected to a single-element-varying, voltage-driven Wheatstone bridge, which is composed of three 700kOhm non-variable resistors and the piezoresistive sensor as the varying element. The output of the bridge is fed to an instrumentation amplifier (INA122, Texas Instruments) with a gain of 6.

An estimation of the resonant frequency of the sensor is around 100Hz; therefore, the sampling rate of the microcontroller is configured as 500Hz. After the microcontroller has sampled and stored 20 sampled data points in its internal memory, the peak-to-peak
vibration amplitude of the output voltage is derived from this data set by determining the difference between the maximum and minimum values in the stored data. Seven of these peak-to-peak measurements are then averaged to produce the final output of the sensor read-out circuitry, which indicates the flow-induced vibration amplitude. The average of the output will filter the noise while preserving the signal. A digital or analog band pass filter with center frequency around 100Hz can also be added to filter the noise. However, additional computation or circuitry is needed, which will result in added complexity in either software or hardware.

![Flow sensor schematic](image)

*Single-element-varying, voltage-driven Wheatstone bridge*

Figure 96. Schematic illustration of sensor readout circuit and implementation of vibration amplitude measurement method
Figure 97. Output of the all-polymer flow sensor from the proposed vibration-amplitude measurement method: Reference wind velocity (upper) and the measured sensor response (lower). (The sensor output voltage is proportional to the amplitude of the sensor vibration.)

A high-sensitivity single cantilever sensor is tested using the new measurement method. Figure 97 shows the sensor output response after the readout circuitry and the reference sensor output as the air flow is repetitively cycled between 0m/s and 12m/s. The results show that the baseline drift which is observed in conventional direct measurement method, shown in Figure 1, has been greatly reduced. The maximum value of the sensor output is 225mV when the wind velocity is 12m/s. Although the sensor exhibits a threshold behavior and is sensitive to velocities only in the range of 5-12m/s,
this range is adjustable by changing the geometry of the sensor. The sensor is also tested without applying wind velocity to characterize the zero-input drift as shown in Figure 98. The standard deviation of the sensor output from one-hour data acquisition is 2.8mV, which corresponds to a flow-referenced drift error of 0.2m/s wind velocity per hour. Figure 99 shows the measured vibration amplitude of the all-polymer flow sensor when the wind velocity varies between 0m/s and 16m/s. With an amplifier gain of 6 and a Wheatstone driving voltage of 5.12V, the sensitivity of the sensor measures 14.5mV/(m/s), with non-linearity of 1% over the range of 5-16m/s wind velocity.

![Graph](image)

*Figure 98. Zero-input drift of the all-polymer flow sensor as a function of time using the reduced-drift measurement approach.*
Figure 99. Sensor output as a function of the wind velocity, acquired by the vibration amplitude measurement method

The dual-cantilever all polymer flow sensor is also tested with the vibration amplitude measurement method. Figure 100 shows the measured output of the fabricated all-polymer flow sensor array using the proposed vibration amplitude measurement. The wind velocity varies between 0m/s and 12m/s. With an amplifier gain of 5 and a Wheatstone driving voltage of 3.33V, the sensitivity is measured to be 13.2mV/(m/s). This measured sensitivity is equivalent to a sensitivity of 24.4mV/(m/s) with an amplifier gain of 6 and a Wheatstone driving voltage of 5.12V, a 68% sensitivity improvement compared with the 14.5mV/(m/s) sensitivity of the aforementioned sensor. In addition,
this improved sensitivity results in a threshold drop from 5m/s to 4m/s as shown in Figure 100. Figure 101 shows the fabricated sensor output response and the reference sensor output when the air flow is repetitively cycled between 4 m/s and 10 m/s. The sensor has demonstrated reduced baseline drift as well as improved minimum air flow velocity detection. Since sensors with different geometries were tested with the proposed measurement method, a comparison is made in Table 18.

![Graph](image.png)

Figure 100. Sensor output as a function of the wind velocity, acquired by the vibration amplitude measurement method
Figure 101. Output of the all-polymer flow sensor from the proposed vibration-amplitude measurement method: Reference wind velocity (upper) and the measured sensor response (lower).
Table 18. Performance characteristics of a typical microtuft-based flow sensor

<table>
<thead>
<tr>
<th></th>
<th>Original geometry</th>
<th>Modified geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device dimension</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single Cantilever:</td>
<td>Dual cantilevers:</td>
</tr>
<tr>
<td></td>
<td>3.5mm (l) × 0.6mm (w)</td>
<td>0.7mm (l) × 50μm (w)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flapper: 0.4mm (l) × 1.1mm (w)</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>14.5mV/(m/s) @ 5.12V gain 6</td>
<td>13.2mV/(m/s) @ 3.33V gain 5</td>
</tr>
<tr>
<td>Threshold</td>
<td>~5m/s</td>
<td>~4m/s</td>
</tr>
<tr>
<td>Non-linearity</td>
<td>1% (5~12 m/s)</td>
<td>4.7% (4~12m/s)</td>
</tr>
<tr>
<td>Zero-input drift</td>
<td>0.2m/s in 1 hour</td>
<td>0.033m/s in 1 hour</td>
</tr>
</tbody>
</table>

4.2.1 Measurement Methods Comparison

Figure 102. Long term drift comparison between direct resistance measurement method and vibration amplitude measurement method. Blue dots: initial measurement data. Purple dots: measurement data after 6 hours. Experiments are done using an all-polymer air flow sensor with optimized geometry

In order to verify the improved characteristics of the proposed vibration amplitude measurement method, the fabricated sensor output is measured using both direct
resistance measurement method and the proposed method. Then the outputs were compared as shown in Figure 102. The sensor is measured twice with 6 hours of measurement interval. Blue dots represent the initial measurement data and the purple dots represent the measurement data after 6 hours. With the direct resistance measurement method, the baseline resistance drift was clearly observed. However, in the experimental results using the vibration measurement method, the blue and purple dots almost fully overlap, which indicates that the drift is significantly reduced. Velocity-referenced baseline drift using the vibration amplitude measurement method was 0.033 (m/s)/hr.

4.2.2 Algorithm for Wireless Sensing

The vibration amplitude measurement algorithm has also been incorporated into the microcontroller-based active sensor system developed in Chapter 2 as shown in Figure 103. The principle is to convert the vibration amplitude into a delay signal $D$, which sets the output frequency of the square wave signal on the I/O pin. The details of the hardware are described in Chapter 2 Section 3 and the code of the algorithm is in Appendix B. The experimental results of the wireless sensing are shown in Figure 104.
Figure 103. Wireless sensing for vibration amplitude measurement method

Figure 104. Wirelessly detected frequency as a function of flow rate
CHAPTER 5
CAPACITIVE PRESSURE SENSOR

With benefits of polymer-based sensors, such as lower material cost and flexibility, it is appealing to develop an all-polymer absolute pressure sensor for absolute pressure measurement in the sensor system described in Chapter 1. However, we still need to address the drift issues in polymer-based sensors. In previous chapters, different methods reduce drift in polymer flow sensors. Will the methods work in a polymer-based absolute pressure sensor? For the flow-induced vibration amplitude measurement method, the answer is “No.” Unlike air flow, air pressure will not induce vibration, which can be used for drift reduction, in the sensor membranes. In the all-polymer flow sensor, the wind velocity-referred drift reduces when the sensitivity of the sensor increases. In an absolute pressure sensor, will high sensitivity reduce the sensor drift as well? An analysis of the gas permeation-induced drift the polymer-based biodegradable absolute pressure sensor in Figure 23 [51] will help to answer this question.

When there is a pressure difference between the outside environment and the hermetically sealed sensor cavity of the biodegradable sensor, the top and bottom metal plates will deflect, which results in a change of the capacitance of the MEMS capacitor. This capacitor, with the inductor around it, forms an LC resonator circuit with a resonant frequency \( f \) given by:

\[
\frac{1}{2\pi \sqrt{LC}} \quad \text{(5.1)}
\]

where \( L \) is the inductance of the inductor, and \( C \) is the capacitance of the capacitor. The pressure difference, which results in variation of \( C \) and \( f \), is also a driving force to move
gas molecules into the cavity of the sensor. Unless the pressure inside the cavity is equal to the pressure in the outside environment, this movement will never stop. The permeability coefficient \( k \) describes the ability of gas to penetrate through a polymeric membrane is given by Equation (1.4). Rewriting (1.4) gives:

\[
\Delta p = \frac{1}{k} \frac{t}{A} q
\]  

(5.2)

If we compare Equation (5.2) with Ohm’s law given by:

\[
V = \rho \frac{l}{A},
\]

(5.3)

where \( V \) is the voltage, \( I \) is the current, \( \rho \) is the resistivity of the material, \( l \) is the length of the resistor, and \( A \) is the area of the material of the resistor, we can make an analogy between these two physical phenomena. In both phenomena, a driving force (voltage \( V \) or pressure difference \( \Delta p \) ) generates a flow (current \( I \) or gas flow \( q \) ). The material conducting this flow has a resistance to the flow, which is proportional to the length of the material and inversely proportional to the area. Therefore, the equivalence is given by:

\[
\Delta p \rightarrow \Delta V
\]

\[
q \rightarrow I
\]

\[
\frac{1}{k} \rightarrow \rho
\]

\[
\frac{1}{k} \frac{t}{A} \rightarrow R
\]  

(5.4)

Another equivalence we can make is that the cavity of the sensor is equivalent to a capacitor. The integration of flow \( q \) is the total volume \( \text{vol} \) (at atmospheric pressure \( P_{\text{atm}} \)) that penetrates into the cavity of the sensor given by:
\[ vol = \int q \, dt \]  
\[ (5.5) \]

If we assume the temperature does not change,

\[ vol \times P_{atm} = vol_{cavity} \times P_{cavity}, \]
\[ (5.6) \]

where \( vol_{cavity} \) is the volume of the cavity and \( P_{cavity} \) is the pressure inside the cavity of the sensor, we have

\[ P_{cavity} = \frac{\int q \, dt}{vol_{cavity}} \div \frac{1}{P_{atm}}. \]
\[ (5.7) \]

Comparing it with the voltage and current relationship in a capacitor \( C \), given by

\[ V = \frac{1}{C} \int I \, dt, \]
\[ (5.8) \]

yields the equivalence as follows

\[ \frac{vol_{cavity}}{P_{atm}} \rightarrow C. \]
\[ (5.9) \]

With these equivalences, we can model the sensor structure with an RC circuit when calculating the pressure change inside the sensor cavity as a result of gas permeation. In an RC circuit, \( \Delta V(t)/Vin \), where \( \Delta V(t) \) is the difference between the input voltage and the voltage of the capacitor, is related to the time constant \( RC \) as

\[ e^{-t/RC} \]
\[ (5.10) \]

Therefore, with the equivalence, the \( \Delta P(t)/P_{ext} \), where \( \Delta P(t) \) is the pressure difference between the pressure exterior to the sensor \( P_{ext} \) and the pressure inside the cavity of the sensor, is related to the time constant \( R'C' \) as

\[ e^{-t/R'C'}. \]
\[ (5.11) \]
where $R'$ and $C'$ are the equivalent R and C respectively.

Turning the gas permeability model into a circuit model helps us both intuitively understand the physical phenomenon and simplify the calculation. Furthermore if we have a more complicated system with more “resistors” and “capacitors,” this method allows us to simulate the system with Spice, a well-developed CAD tool for electrical systems. The modeling procedure of the gas permeation issue of the sensor is to 1) calculate the equivalent $R'$ and $C'$ in the sensor system, 2) derive the $R'C'$ time constant, and 3) derive the pressure difference $\Delta P(t)$ with the $R'C'$ constant. Table 19 lists the permeability of $N_2$ in PLA [54], the sensor dimension, equivalent $R'$ and $C'$ values, and the equivalent RC constants. Figure 105 shows the pressure difference variation as a function of time. The pressure difference continuously decreases with a time constant of 2923 hours.

The theoretical pressure difference drop in 2.3 hours is 0.08%, while experiments measuring the drift $fo$ show a 0.26% resonant frequency drift, which is equivalent to a pressure difference drop of around 2%, around twice the theoretical drift value. This discrepancy might be due to leakage paths on the interface between PLA and metal plates as a result of imperfections in sensor fabrication.

<table>
<thead>
<tr>
<th>Parameters for gas permeability calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>K(Barrer)</td>
</tr>
<tr>
<td>0.05[54]</td>
</tr>
</tbody>
</table>
The analysis results show that in the polymer pressure sensor, the gas permeation in the sensor cavity results in a drift. If the pressure difference $\Delta P$ is positive, gas molecules start penetrating the polymer spacer into the sensor cavity, resulting in a decrease in the pressure difference $\Delta P$ with an RC time constant. As more and more gas goes into the cavity, the pressure inside the chamber rises until the pressure difference $\Delta P$ becomes zero. At this moment, even if we have an infinitely sensitive pressure sensor, the sensor response will still be the baseline capacitance.

Since the gas-permeation-induced drift of a polymer pressure sensor cannot be solved by either the new measurement method or increasing the sensitivity of the sensor, the choice left is to use a material that can hermetically seal the sensor cavity. In the literature, silicon demonstrates superior performance in maintaining a hermetically sealed cavity [52]. In this research, to maintain the benefit of polymer-based sensors while
addressing the permeability issue of the polymer materials in a polymer-based absolute pressure sensor, a tiny silicon pressure reference will be fabricated and embedded in a flexible polymer substrate.

5.1 Sensing Principle and Sensor Design

The illustration and principle of the capacitive pressure sensor is shown in Figure 106. The capacitive pressure sensor is comprised of two silicon membranes and a silicon dioxide spacer. As pressure changes, the silicon membranes deflect, which causes sensor capacitance changes.

Figure 106. Illustration of the capacitive pressure sensor
Figure 107 shows the top view of the capacitive pressure sensor. The sensor is square because it is more sensitive than a rectangular sensor [78]. Suppose the four edges of the diaphragm are clamped and the deflection $D(x, y)$, when a pressure $P$ is applied, is small compared to thickness $h$; the following differential equation governs the deflection [78]:

$$\frac{\partial^4 D}{\partial x^4} + 2\alpha \frac{\partial^4 D}{\partial x^2 \partial y^2} + \frac{\partial^4 D}{\partial y^4} = \frac{P}{D_0 h^3}$$  

(5.12)
where $\alpha = 0.798$ and $D_0=14.2\text{GPa}$ with the plate faces $<100>$ oriented and sides $<110>$ oriented. The boundary conditions are

$$D\left( x = \pm \frac{a}{2}; y \right) = 0$$
$$D\left( x; y = \pm \frac{a}{2} \right) = 0$$
$$\frac{\partial D}{\partial y} \left( x = \pm \frac{a}{2}; y \right) = 0$$
$$\frac{\partial D}{\partial x} \left( x; y = \pm \frac{a}{2} \right) = 0$$

(5.13)

In [78], an approximated analytical solution is given by solving the differential equation using the Galerkin method:

$$D(0,0,P) = D(0,0,P) F(X,Y),$$

(5.14)

where

$$D(0,0,P) = \frac{0.02126a^4}{16D_0 h^3} P$$

(5.15)

$$F(X,Y) = \left[ \left( 1 - X^2 \right) \left( 1 - Y^2 \right) \right]^2 \sum_{i=0}^{n} \sum_{j=0}^{n} k_{ij} X^i Y^j$$

(5.16)

Table 20. Values of coefficients $k_{ij}$ [78]

<table>
<thead>
<tr>
<th>$k_{00}$</th>
<th>$k_{20}$</th>
<th>$k_{02}$</th>
<th>$k_{22}$</th>
<th>$k_{40}$</th>
<th>$k_{04}$</th>
<th>$k_{42}$</th>
<th>$k_{24}$</th>
<th>$k_{44}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.233</td>
<td>0.233</td>
<td>0.252</td>
<td>-0.00166</td>
<td>-0.00166</td>
<td>0.13</td>
<td>0.13</td>
<td>-0.235</td>
</tr>
</tbody>
</table>

The sensor initial capacitance is given by

$$C(0) = \varepsilon_0 \varepsilon_r \left( \frac{b^2 - a^2}{g} \right) + \varepsilon_0 \frac{a^2}{g}$$

(5.17)

where $\varepsilon_0$ is the vacuum permittivity ($\varepsilon_0 = 8.85 \times 10^{-12} \text{F/m}$) and $\varepsilon_r$ is the relative permittivity of silicon dioxide ($\varepsilon_r = 3.9$).
The total capacitance under a pressure $P$ is [78]

$$
C(P) = \varepsilon_0 \varepsilon_r \left( \frac{b^2 - a^2}{g} \right) + \varepsilon_0 \frac{a^2}{g} \left[ \int_0^1 \int_0^1 \int_0^1 \frac{dXdY}{P} \left( 1 - \frac{dXdY}{16D_0 \frac{dh^3}{0.02126a^4}} \right) F(X,Y) \right]
$$

(5.18)

Many trade-offs exist in designing the pressure sensor. Since the silicon pressure reference is to be embedded in a polymer substrate, a larger size will make the sensor easier to handle and manipulate. However, increasing the size also translates to a higher cost and smaller yield. The top plate thickness $h$ plays an important role in sensor sensitivity and linearity. A larger plate thickness brings better linearity; however, the sensitivity decreases (Figure 108).

![Figure 108. Simulation results of the sensor normalized capacitance as a function of pressure change (from bottom to top: $h$=30µm, 25 µm, and 20 µm)](image)
The gap distance between the top plate and bottom is also a critical parameter in designing the pressure sensor; as the gap increases, the sensitivity decreases. However, the linearity is proportional to the gap distance (Figure 109).

![Figure 109. Simulation results of the sensor normalized capacitance as a function of pressure change (from bottom to top: g=1.2 µm, 1 µm, and 0.8 µm)](image)

Table 21. Parameters of the silicon capacitive reference

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$a$(mm)</th>
<th>$b$(mm)</th>
<th>$h$(µm)</th>
<th>$g$(µm)</th>
<th>$h_b$(µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>1.6</td>
<td>2.2</td>
<td>25</td>
<td>1</td>
<td>550</td>
</tr>
</tbody>
</table>

Table 21 shows the design parameters of the silicon pressure reference. The design is a compromise between size, linearity, and sensitivity. A 2.2mm square size silicon reference makes the handling easier during fabrication and embedding in a polymer substrate. A pressure reference with a 25um top silicon plate thickness and a 1um gap demonstrates a good compromise between sensitivity and linearity (see Figure 110).
Figure 110. Simulation results of the sensor capacitance variation as a function of pressure change with the design parameters in Table 21

5.2 Device Fabrication

5.2.1 Fabrication of the Silicon Pressure Reference

The fabrication process of this pressure sensor is shown in Figure 111. A low-resistivity silicon wafer is first thermally oxidized and patterned (Figure 111(a)). Then the wafer is fusion-bonded to another low resistivity silicon wafer (Figure 111(b)). The
top membrane is then fabricated with a sequence of etching steps illustrated in Figure 111 (c, d and e). Finally the silicon wafer is diced, resulting in a tiny, hermetically-sealed pressure sensor.

The wafers for the pressure reference fabrication are $<1\ 0\ 0>$ N type silicon wafers with a resistivity less than 0.004Ω·cm. The wafers are first cleaned in the Piranha solution, which is a mixture of sulfuric acid and hydrogen peroxide. The wafers are immersed in the Piranha solution for 20mins at 120°C, and then they are cleaned with DI water. Then the wafers are dipped in HF solution and cleaned in DI water. The wafers are then put in a furnace (Tystar) for wet thermal oxide growth at 1100°C for around 2 hours 15minutes, resulting a thermal oxide of around 1µm thickness. Both top and bottom oxide layers are patterned. Karl Suss MA-6 Mask (Karl Suss Inc.) aligner is used for alignment and exposure. The photolithography recipe is shown in Appendix A.

Since both top and bottom patterns need to be aligned, backside alignment (BSA) has been applied. Figure 112 shows the alignment chunk for BSA. During the BSA, a camera underneath the holes on the chunk takes a picture of the backside of the wafer. The mask is then compared and aligned with the picture of the backside of the wafer. Figure 113 shows pictures of patterned oxide on both sides of the wafer after BSA.
Figure 112. Chunk for backside alignment

Figure 113. Oxide patterns on both side of the silicon wafers; left (lower side), right (upper side)

Once the silicon dioxide patterning is done, the patterned wafer is cut into pieces and fusion-bonded with other wafer pieces. The fusion bonding starts with an RCA clean of the wafer pieces to be bonded to guarantee residue-free surfaces. These wafer pieces then experience O₂ plasma activation in Vision 320 RIE (Advanced Vacuum). Table 22 lists the recipe for O₂ plasma activation. Compare to other RIE process such as oxide etching or descum process, the power is relatively low to minimize the physical damage and maintain a flat surface on the wafer pieces during O₂ activation. After the RIE process, the wafer pieces are stacked and pressed using tweezers to give an initial
bonding. Then, the stacked wafer pieces are put on a chunk, which will be loaded into SB6 wafer bonder (Karl Suss Inc.), where the wafer pieces experience pressure of 3000mbar and temperature of 250°C for 8 hours. The next step is to put the wafer pieces into a furnace (Tystar) to anneal them at 900°C in N₂ ambient.

Table 22. Recipe for the O₂ plasma activation

<table>
<thead>
<tr>
<th>Pressure (mT)</th>
<th>Gas O₂ (sccm)</th>
<th>Power (W)</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>10</td>
<td>100</td>
<td>15</td>
</tr>
</tbody>
</table>

**Figure 114. Wafer pieces to be bonded on the chunk of SB6 bonder**

These annealed wafer pieces are then mounted on a carrier wafer for silicon etching in the STS ICP. The etched silicon piece is shown in Figure 115. This etching step defines the thickness of the top membrane (Figure 111 (c)). After the silicon etching step, the oxide mask is dry etched (Figure 111 (d)) in the Vision 320 RIE. Finally the silicon pieces with oxide removed are put in STS ICP again for top membrane release (Figure 111 (d)). With the top membrane released, the silicon piece (Figure 116) is ready to be diced. For dicing silicon pieces, a blue adhesive tape is used to hold the pieces during diamond saw cutting. Photoresist (AZ4620) is coated on the silicon wafer to protect the top membrane from shock or vibration during the dicing process. Figure 117
shows the diced silicon pressure references with photoresist covered and Figure 118 is an SEM picture of the diced pressure reference with photoresist removed.

Figure 115. Silicon pressure reference after the first ICP etching

Figure 116. Silicon pressure references to be diced.
Figure 117. Diced silicon references

Figure 118. SEM picture of a diced silicon pressure reference
5.2.2 Polymer Substrate Fabrication and Silicon Reference Embedding

Eventually the silicon pressure reference will be embedded in a flexible substrate, which is a Kapton® sheet (125µm) laminated with a copper sheet (35µm) with cavities for embedding (Figure 119 (a)). The Kapton® sheet is first CO₂ laser micromachined, and then laminated with the copper sheet via a Teflon® FEP film (Dupont). The Kapton® and copper sheet are laminated in the bench-top laminator with temperature (280°C) and pressure (200psi). After the laminated flexible substrate cools down, a drop of silver epoxy is dispersed in each cavity to interconnect the silicon reference with the bottom copper sheet. Then, the silicon references are dropped in the cavity with tweezers, followed by a curing at 120°C for 1 hour in an oven. Next photoresist will be dispersed on the Kapton® sheet using a pipette. Because the silicon pressure reference is taller than the Kapton® sheet, a low spin speed of 300rpm will disperse the photoresist on the substrate without covering the silicon reference. The purpose is to avoid photolithography, which might result in damage to the sensor top membrane. Figure 121 shows a four sensor array with the silicon pressure references embedded. To interconnect
the top membrane, either metallization or a conductive epoxy can be used. In this research, silver epoxy has been used for prototyping.

Figure 120. Fabricated flexible substrate with a lamination process

Figure 121. Silicon pressure reference embedded in the flexible substrate

5.3 Sensor Characterization

A fabricated sensor was tested in a pressure chamber as shown in Figure 122. The pressure chamber is connected with a gas tank and the chamber pressure is controlled by
a regulator. The sensor capacitance is measured by an RLC meter (Keithley 3322), while the chamber pressure is measured using a commercially available pressure sensor (Fluke PV350).

![Experimental setup for pressure measurement of the capacitive sensor](image)

Figure 122. Experimental setup for pressure measurement of the capacitive sensor

Figure 123 shows the sensor capacitance variation as a function of pressure variation for both simulation results (circle) and measurement results (cross). The x-axis shows the differential pressure over atmospheric pressure, which is measured by the reference pressure sensor. The fabricated sensor also measures the differential pressure because, during fabrication, air was sealed in the capacitive sensor. The sensor demonstrates sensitivity around 0.6%/kPa. The measurement results agree with the
simulation results, with an increase in the baseline capacitance, which is contributed to by the stray capacitance.

In order to measure the baseline capacitance drift, the sensor is measured again after one week. The measurement results are shown in Figure 124. The baseline capacitance drift is 0.6pF.

![Figure 123. Sensor response as a function of pressure change (differential pressure over atmospheric pressure.). circle: simulation results, cross: measurement results](image)

![Figure 124. Sensor response as a function of pressure change(one week later)](image)
If the SiO$_2$ spacer is made out of PLA, how much will the sensor drift? Table 23 shows the parameters relating to the permeability of the sensor with PLA as the spacer. The simulation result in Figure 125 shows that, after 144 hours, the pressure difference drops to 19.4% of its original value. Assuming the test chamber pressure maintains at around 9kPa, after 144 hours, the pressure difference between inside and outside the sensor cavity becomes around 1.7kPa, which results in a sensor output of 72.8pF (Figure 126).

Table 23. Parameters of the permeability of the sensor

<table>
<thead>
<tr>
<th>K(Barrer)</th>
<th>a(mm)</th>
<th>Gap(cm)</th>
<th>Area(cm$^2$)</th>
<th>t(cm)</th>
<th>R$'$</th>
<th>C$'$</th>
<th>RC(hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05[54]</td>
<td>0.16</td>
<td>0.0001</td>
<td>0.000064</td>
<td>0.03</td>
<td>9.38$\times$10$^{13}$</td>
<td>3.37$\times$10$^{-9}$</td>
<td>87.7</td>
</tr>
</tbody>
</table>

Figure 125. Theoretical results of pressure differences between the exterior and the interior of the sensor with a polymer spacer as a function of time
The theoretical results shown in Figure 125 and Figure 126 demonstrate that, in a polymer pressure sensor with a sensor spacer made out of PLA, a large drift will occur in 144 hours. By applying the proposed solution—that is, by embedding a silicon reference in a polymer substrate—the sensor drift can be greatly reduced compared to the theoretical value. To measure the drift induced by gas permeability of the silicon-reference-embedded sensor, the test chamber pressure was regulated at around 9 kPa, and sensor capacitance was tracked during a week. Figure 127 shows the permeability test result: instead of a predicted sensor output drop in the polymer pressure sensor, the silicon-pressure-reference-embedded polymer-based sensor shows a stable output when the test chamber pressure maintains around 9 kPa (Figure 127) (The pressure shows a slight drop because of the non-ideal regulator.).
In Chapter 2, a microcontroller-based wireless sensor system is built for the all-polymer flow sensor. An oscillator-based wireless sensor system is built for the pressure sensor in this chapter. Figure 128 shows the principle of this system, which converts the capacitance change of the pressure sensor into a frequency change through an astable multivibrator. The oscillation frequency of the multivibrator, if \( R_1 = R_2 \), is \( \frac{1}{2RC \ln 3} \). When the sensor capacitance varies as pressure changes, the oscillator frequency of the multivibrator also shifts. The spectrum analyzer will detect this frequency change wirelessly.

Figure 129 shows the experimental setup. The pressure chamber setup is the same as the setup described in the previous section. A breadboard is used to build the oscillator, with comprises an opamp (OPA551, Texas Instruments) with a +/-5 V power supply and three 215kΩ resistors. The output of the oscillator is connected with a coil and a 1k resistor to limit the coil current. The spectrum analyzer, with its antenna coil, detects the frequency change of the oscillator wirelessly. Both the coils and the spectrum
The analyzer used in this experiment are the same as those described in the wireless sensor system in Chapter 2. Figure 130 shows the experimental results of the wireless sensing measurement. The frequency decreases as pressure increases with a sensitivity of around 0.5%/kPa.

![Block diagram of the oscillator-based wireless system](image)

Figure 128. Block diagram of the oscillator-based wireless system
Figure 129. Wireless sensing setup for the silicon-reference-embedded pressure sensor

Figure 130. Wirelessly-detected frequency variation as a function of pressure change
CONCLUSION

In nature, flow sensors such as the hairs of a cricket are vital to the survival of insects because it allows them to sense flow and vibration. Although the sensitivity of these tools from nature amazes us, we are not always aware of their robustness. These sensors bend, experience shocks, and wear off during the life time of insects. However, they continuously sense the environment and provide them with important information that ensures their survival.

When designing sensors to operate in harsh environments, designers must account for robustness. If flow sensor designers place robustness ahead of sensitivity, then they will view the design in an entirely different way. For one, they will not consider silicon the best material because it is so brittle. Reducing the brittleness of sensor structures requires that the long and thin silicon cantilever beam with high sensitivity be replaced by a shorter and thicker one. However, with the reduction in sensitivity, the design needs to improve the sensor interface electronics so that they compensate for this sensitivity loss, for example, by increasing the gain of an amplification stage, reducing noise, and increasing the ADC accuracy. Therefore, from a system point of view, a short and thicker silicon cantilever beam does not have to have low sensitivity compared to its long and narrow counterpart. However, a short and wider silicon beam is more robust.

To design a robust flow sensor, polymer material, because of its flexibility, is a good choice. However, the choice of designing a polymer sensor often means sacrificing accuracy. The accuracy of the polymer sensor is much lower than its silicon counterpart because of aging, viscoelasticity, moisture absorption, and gas/liquid permeability. These
properties associated with polymers originate from their molecular construction. Therefore, if designers choose a polymer material for a flow sensor design, they have to deal with all these material properties. In terms of sensor performance, these properties will all contribute to sensor drift, for instance, the baseline resistance in an all-polymer piezoresistive flow sensor and drift resulting from gas permeation in a polymer pressure sensor.

This research proves that we can use flow-induced vibration to measure the flow rate with reduced sensor drift. This drift reduction measurement method, the vibration amplitude measurement method, is believed to be applicable to flow sensors with other sensing principles such as capacitive flow sensors. Furthermore, the idea of sensing an AC signal for drift reduction can be applied to areas other than flow sensing. The main drawback of this measurement method is that it works at a flow rate above critical flutter velocity. This limitation requires sensor designers to use sensor material and a structure that extend the minimum detectable flow rate. In this research, sensor material, the structure, and sensor fabrication are co-designed, which is critical for process simplification resulting in lower cost, higher yield, and shorter fabrication time. In the co-design, the dual-cantilever sensor structure allows self-alignment in fabrication, and using a Pt thin film as the piezoresistor, the etching mask, and the layer, which induces an out-of-plane structure, results in a two fabrication-step process, the simplest fabrication process ever developed for a MEMS flow sensor.

To design a sensitive flow sensor of the types described in this thesis, the following guidelines can be considered. First, determine the maximum possible length of the sensor, which depends on applications. Second determine the minimum thickness of
the sensor, which largely depends on fabrication processes and robustness requirements of the sensor. Generally a smaller thickness results in difficulties in fabrication and loss of robustness. As discussed in the sensor modeling part, a longer and thinner cantilever has a higher sensitivity. If the maximum length and minimum thickness are chosen for the flow sensor, the sensor will demonstrate the highest sensitivity. However, there is a trade-off between sensitivity and the maximum detectable flow rate, at which the flow sensor saturates. The more sensitive the sensor is, the smaller the maximum detectable flow rate (dynamic range) will be. If maximum detectable flow rate is too small, then the sensor length can be reduced and/or thickness can be increased. In the dual-cantilever design, the width of the dual-cantilever and the area of the flapper can also be adjusted to achieve a compromise between sensitivity and maximum detectable flow rate. Reducing the width of the dual cantilever and increasing the area of the flapper result in sensitivity enhancement. However, the sensor will saturate at a lower wind velocity.

Nature developed incredible “all-polymer” flow sensors with the “fabrication process” of “survival of the fittest.” For flow sensor designers, the best choice may be to use nature-developed flow sensors constructed by hairs and neurons and to interface them with electronics. Advances in MEMS technology, bio-engineering and neuron interfacing technology are making these sensors possible.
APPENDIX A

RECIPE OF LIFT-OFF PROCESS

1. Spin coating AZ4620 photoresist:
   500rpm/100rpm step 10secs, 3000rpm/1000rpm step 40secs

2. Soft bake in oven at 100°C for 30mins

3. Exposure dose: 500mJ

4. Photoresist develop solution preparation:
   One volume AZ400k with two volumes DI water.

5. Slightly shake the container for develop until no crimson flow coming out

6. O₂ RIE for 15 sec to remove the photoresist residue

7. E-beam evaporation of metal

8. Immerse the sample in acetone until photoresist lifts and patterns appear
MICROCONTROLLER CODES

// C codes of the MSP430 microcontroller

#include "msp430xG46x.h"

volatile unsigned int p;
unsigned int r[20];
unsigned int a[7];
unsigned int b[7];
unsigned int r1[10];
unsigned int r2[10];
unsigned int samplevalue;
unsigned int max;
unsigned int min;

void sample()
{
  for(int i=1;i<85;i++)
  {
  }

  ADC12CTL0 |= ADC12SC;    // Start sampling/conversion
  ADC12MEM0*0.61;

  ADC12IE = 0x01;           // Enable interrupt

  void main(void)
  {
    WDTCTL = WDT + WDTHOLD;  // Stop WDT
    ADC12CTL0 = REFON+REF2_5V+ADC12ON + SHT0_2;  // Sampling time, ADC12 on
    ADC12MCTL0=SREF_1;
    for(p=0x7000;p;p--);
    ADC12IE = 0x01;           // Enable interrupt
ADC12CTL0 |= ENC;
P6SEL |= 0x01;                        // P6.0 ADC option select
P3DIR |= 0xF1;                        // P5.1 output
P3OUT |= 0x00;

for(;;)
{
  for(int y=0;y<10;y++)
  {
    for(int m=0;m<7;m++)
    {
      for(int k=0;k<20;k++)
      {
        P3OUT &= ~0xF0;
        sample();
        r[k]=samplevalue;
      }
      max=0;
      for(int n=0;n<20;n++)
      {
        if (r[n]>max)
          max=r[n];
      }
      min=2500;
      for(int n=0;n<20;n++)
      {
        if (r[n]<min)
          min=r[n];
      }
      a[m]=max-min;
      b[m]=0;
      b[m]=0.5*(max+min);
    }
    int ampli;
    //ampli=0.5*r1[y]; // Vibration amplitude measurement method
    ampli=0.2*r2[y]; // Direct measurement method
    int average;
    average=r2[y];
    
    FLL_CTL0 |= DCOPLUS + XCAP18PF; // DCO+ set, freq = xtal x D x N+1
    SCFI0 |= FN_4; // x2 DCO freq, 8MHz nominal DCO
SCFQCTL = 121;

int period=1000;

switch(ampli)
{
  case 10:
    for(int k=0; k<period;k++)
    {
      P3OUT = 0xF0;
      __delay_cycles(10);
      P3OUT = 0xF1;
      __delay_cycles(10);
    };break;
  case 11:
    for(int k=0; k<period;k++)
    {
      P3OUT = 0xF0;
      __delay_cycles(11);
      P3OUT = 0xF1;
      __delay_cycles(11);
    };break;
  case 12:
    for(int k=0; k<period;k++)
    {
      P3OUT = 0xF0;
      __delay_cycles(12);
      P3OUT = 0xF1;
      __delay_cycles(12);
    };break;
  ...
  case 130:
    for(int k=0; k<period;k++)
    {
      P3OUT = 0xF0;
      __delay_cycles(130);
      P3OUT = 0xF1;
      __delay_cycles(130);
};break;

default:
    for(int k=0; k<10000;k++)
    {
        P3OUT = 0xF0;
        __delay_cycles(100);
        P3OUT = 0xF0;
        __delay_cycles(100);
    };break;

#pragma vector = ADC12_VECTOR
__interrupt void ADC12_ISR(void)
{
    if (ADC12MEM0 >= 0x7ff) // ADC12MEM = A0 > 0.5AVcc?
        P5OUT |= 0x02; // P5.1 = 1
    // else
    // P5OUT &= ~0x02; // P5.1 = 0

    __bic_SR_register_on_exit(LPM0_bits); // Exit LPM0
}
REFERENCES


Chao Song was born in Shanghai, China. He received a B.S. degree in electrical engineering from Shanghai Jiaotong University in 2004. In 2007, he obtained his Dipl.-Ing in electronics and signal processing and an M.S. degree in microelectronics and microsystems from ENSEEIHT, Toulouse, France. In 2008, he received his M.S. degree in electrical and computer engineering from Georgia Institute of Technology and started working toward his Ph.D. degree in the research group of Professor Mark G. Allen. His research includes MEMS flow and pressure sensors, implantable pressure sensors, sensor interface circuits, and neuron interfacing devices.

From 2004 to 2005, he worked in Chinese Academy of Science Shanghai Institute of Microsystem and Information Technology in the area of sensor network. In 2006, he interned in SIEMENS VDO, Toulouse, France, testing and evaluating a position sensor for automobile. In 2007 he interned in Research Center of Spatial Ray, Toulouse, France, designing interfacing ICs for radiation detection sensors. In 2008, he became a research assistant in Georgia Institute of Technology, Atlanta, Georgia. From August 2013 till December 2013, he was a design intern in Linear Technology Corporation, Milpitas, California, working on power management ICs. From June 2014, he joined Qualcomm Corporation, San Diego, California, as an IC designer.