A Micromechanical Parylene Spiral-Tube Sensor and Its Applications of Unpowered Environmental Pressure/Temperature Sensing

Po-Jui Chen and Yu-Chong Tai
Micromachining Laboratory, California Institute of Technology
Pasadenca, CA, USA
pjchen@mems.caltech.edu

***Abstract*—A multi-function micromechanical pressure/ temperature sensor incorporating a microfabricated parylene spiral tube is presented. Its visible responses in expression of *in situ* rotational tube deformation enable unpowered sensing directly from optical device observation without electrical or any powered signal transduction. Sensor characterizations show promising pressure (14.46°/kPa sensitivity, 0.11 kPa resolution) and temperature (6.28°/°C sensitivity, 0.24 °C resolution) responses. Depending on different application requests, this sensor can be individually utilized to measure pressure/temperature of systems having one property varying while the other stabilized, such as intraocular or other *in vivo* pressure sensing of certain apparatus inside human bodies or other biological targets. A straightforward sensor-pair configuration has also been implemented to retrieve the decoupled pressure and temperature readouts, hence ultimately realizes a convenient environmental pressure and temperature sensing in various systems.**

I. Introduction

Pressure and temperature are generally the most two significant properties in most physical, chemical, and biological systems. Utilizing sensors to measure these properties provides a viable and crucial means of conditioning the systems of interest. Along the researches toward sensor development and implementation, microscaled sensors have attracted more and more attentions as they have excellent sensing performance compared with traditional ones and, more importantly, occupy a small volume, which has a great potential for their integration with target systems, especially in handheld and implanted types [1].

Among all kinds of microsensors, unpowered mechanical and physical sensors are valuable for their simplicity, obviation of signal transduction/acquisition and power consumption, and ease of use. These advantages give such sensors the possibility to be widely used in appropriate environmental monitoring with moderate sensitivity requirements. The unpowered microsensors are typically realized using micromechanical elements, for example, bi-metallic structures for temperature sensing. The mechanical responses of the sensors in existing designs, however, are not substantial in most cases due to the fact that they heavily depend on scaling effects. This difficulty at the end hinders their real applications. Therefore, our goal in this work is to develop an unpowered microsensor totally excluding electronic acquisition while having satisfactory sensing performance for its ultimate use in environmental monitoring of the systems where power/battery is a concern.

To accomplish this objective, a micromechanical spiral-tube sensor has been successfully developed with demonstration of its unpowered pressure sensing behavior by solely using optical observation [2]. In this paper, the temperature behavior of the sensor is extensively studied. After discovered susceptible to both pressure and temperature, different sensing paradigms with the use of this multi-function sensor can be exploited to fulfill suitable pressure/temperature monitoring in different circumstances. Successful proof the concept through a suite of device testing verifies the feasibility of implementing such microdevice with a wide range of environmental sensing applications.

II. Design

A. *Single-Sensor Configuration*

The described micromechanical sensor embodies a high-aspect-ratio free-standing tube structure in spiral geometry (Fig. 1). This conformation enables an angular tube deformation because of a bending moment generated from a pressure difference applied between inside and outside of the tube. With the amplified mechanical deformation attributed to the spiral geometry, this in-plane tube rotation can be qualitatively measured by direct optical observation of the relative position between the end pointing tip and the surrounding indicators. Accordingly, this device can serve as a gauge pressure sensor when the pressure either inside or outside the tube is encapsulated at a predetermined constant as gauge reference. For demonstration the pressure inside the tube is encapsulated at a constant in this work.

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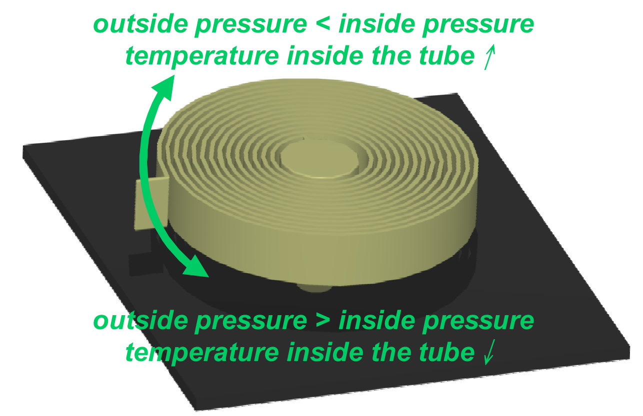

Fig. 1. Concept of the multi-function microsensor. Different directions of tube rotation are resulted from different conditions across the tube.

This spiral-tube sensor also realizes temperature sensing other than its pressure sensing function. When the air inside the tube is sealed, its pressure changes as a function of temperature based on the ideal gas law:

$$PV = nRT$$

Apparently, this effect explains a temperature change inside the tube can lead to a pressure difference across the tube, so that the tube deformation is also correlated with environmental temperature variation, which validates the temperature sensing function of the device. Directions of the spiral tube rotation regarding environmental pressure and temperature variations are denoted in Fig. 1. Even though the sensor is susceptible to both pressure and temperature variations, its application well grounds on monitoring systems that has only one varying parameter while the other stabilized (Fig. 2). Examples include intraocular or other *in vivo* pressure sensing of certain apparatus inside human bodies and other biological targets, in which the temperature inside the system is consistent in normal conditions [3].

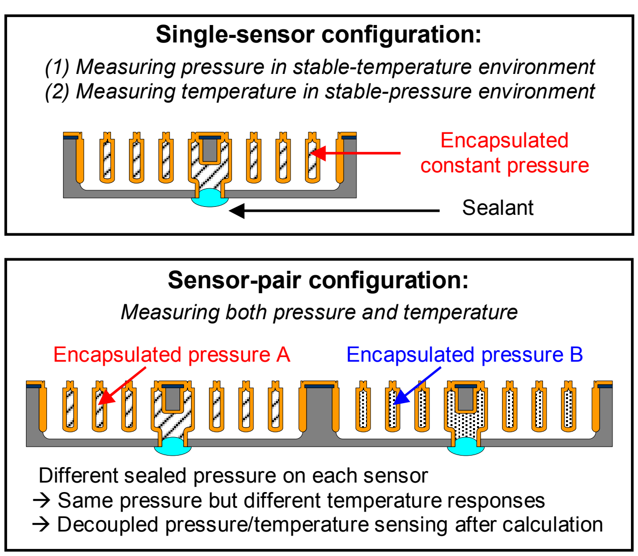

Fig. 2. Different configurations to achieve environmental sensing.

B. *Sensor-Pair Configuration*

Instead of an individual sensor, a pair of identical spiral-tube microsensors can be utilized to facilitate both environmental pressure/temperature sensing in the same system. This configuration illustrated in Fig. 2 involves sealing different pressures on each sensor. These two sensors have the same pressure response due to their gauge pressure rather than absolute pressure sensing mechanism. However, based on the ideal gas law, different pressure variations and associated different tube rotations can be created with the same temperature change. As a result, a two-port model can be built as the following joint equations to represent the sensor-pair behavior:

$$\begin{cases} \Delta\theta_1 = S_P\Delta P + S_{T,1}\Delta T & \text{from sensor 1} \\ \Delta\theta_2 = S_P\Delta P + S_{T,2}\Delta T & \text{from sensor 2} \end{cases}$$

where $\Delta\theta$ is the tube rotation angle, ΔP is the applied pressure difference, ΔT is the applied temperature difference, S_P is the pressure sensitivity, and S_T is the temperature sensitivity. Note the pressure sensitivity is identical for the two sensors ($S_{P,1} = S_{P,2} = S_P$). Consequently, this relation allows correct system pressure and temperature recording from analysis of measured rotational deformation of the sensor pair as long as their pressure and temperature responses are characterized. It is evident that the sensor-pair configuration can be implemented in any system to achieve both environmental pressure and temperature monitoring.

III. Fabrication

Fig. 3 depicts the microsensor fabrication process. It started with growing a 0.75-μm-thick wet oxide on a 4-inch 500-μm-thick double-side-polished silicon wafer. After oxide patterning the backside of wafer was etched with deep-reactive-ion-etching (DRIE) with photoresist as a mask until leaving about 150 μm silicon. This step was to define the access port to inside of the spiral tube. Next, an embedded channel fabrication technology was employed to create the high-aspect-ratio quasi-rectangular channels [4]. Meanwhile, the backside access holes located at the center of the tubes were connected to the parylene channels during the trench etching. This embedded channel technology was accomplished using a single layer of polymer parylene C (poly-para-xylylene C) because parylene coating is completely conformal by its room-temperature chemical vapor deposition (CVD) nature. Parylene was selected also because of its high mechanical flexibility (Young's modulus ~4 GPa) which facilitates greater deformations of the spiral tube structure. After parylene patterning using oxygen plasma with photoresist as a mask and subsequent oxide removal, the parylene tubes were finally released by isotropically etching the silicon with gaseous XeF_2. Using this process 40-mm-long, 17-turn spiral tubes consisting of 190-μm-deep, 12-μm-wide, 3-μm-thick-walled high-aspect-ratio (internal channel height/channel width greater than 30) parylene channels were successfully microfabricated (Fig. 4). Controllable pressures could be sealed in the tubes by applying sealants (e.g. epoxy) to the backside access ports in

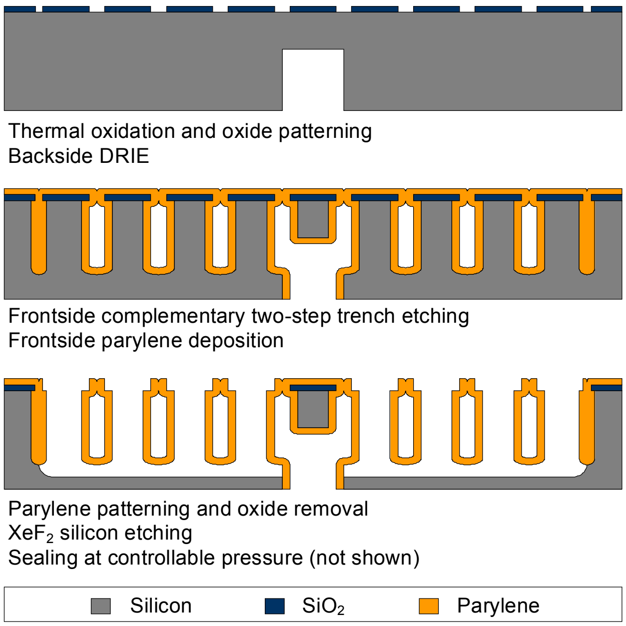

Fig. 3. Fabrication process flow.

different pressurized environments to realize single-sensor and sensor-pair paradigms.

IV. Experimental Setup

In device characterizations well-conditioned testing setups (Fig. 5) were used in order to measure the decoupled pressure and temperature responses of the sensor. The pressure testing setup included a customized pressure regulation system to provide a 0.1 kPa tuning resolution. In the temperature testing, the device was immersed in water to ensure uniform temperature distribution of the parylene spiral tube. The combination of a programmable heat control stage as a heat generation source and a thermal couple as a temperature measurement unit facilitates a 0.1 ^{o}C temperature tuning resolution. For single-sensor testing the

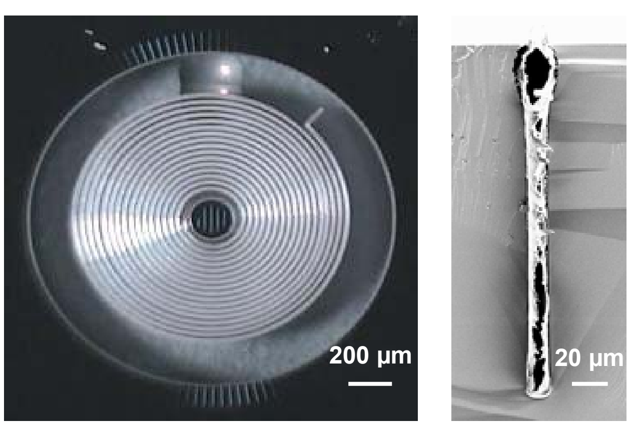

Fig. 4. Microfabricated parylene tube: (Left) Stereoscope image of free-standing parylene spiral tube with surrounding indicators (top view); (Right) SEM image of high-aspect-ratio parylene channel before final release (cross-sectional view). The parylene layer was delaminated due to chip cleavage.

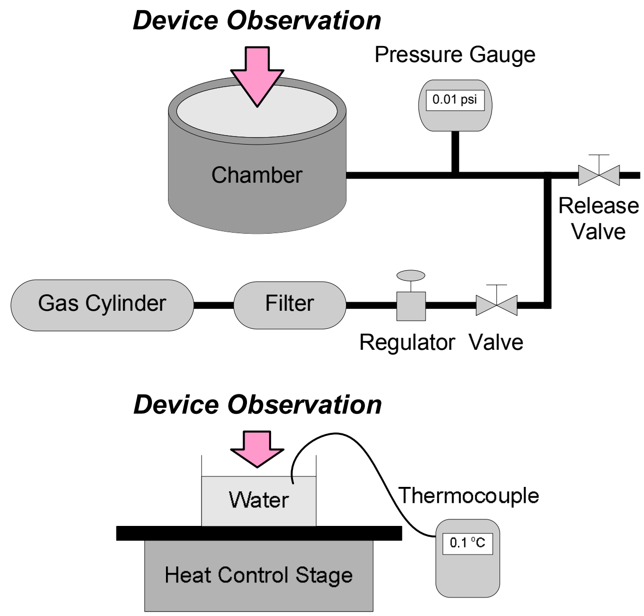

Fig. 5. Schematics of device characterization setups. (Top) Pressure testing; (Bottom) Temperature testing.

parylene spiral tubes were sealed by applying epoxy on the backside access holes under 1 atm at 20 ^{o}C, which act as the gauge reference of pressure and temperature. For sensor-pair testing the two sensors were sealed under different ambient pressures (1 atm and 1.2 atm) at 20 ^{o}C, and the same temperature setup was used to verify the different temperature responses of the sensors. A stereoscope was used to observe the visible tube rotations of the devices in comparison to numerical readouts from the off-chip gauges.

V. Results and Discussion

A. Single-Sensor Characterization

Linear measurement results were obtained in both pressure and temperature testing of the single sensor (Fig. 6), indicating the observed continuous rotational tube deformations in highly linear dependence on both applied pressure and temperature differences. A 14.46^{o}/kPa pressure sensitivity and a 6.28^{o}/^{o}C temperature sensitivity were achieved using the microfabricated parylene spiral tube in the designed geometry described above. Because the temperature difference influences tube deformation by essentially creating intrinsic pressure difference inside the tube, the temperature sensitivity was in good agreement with the pressure sensitivity after conversion using the ideal gas relation. The sensing resolutions were 0.11 kPa in pressure and 0.24 ^{o}C in temperature respectively, constrained by (1) minimum separation distance in between the surrounding indicators, which was 3^{o}/div in the micromachined device, and (2) optical resolution of the observation on the end pointing tip positions. Nevertheless, these testing results demonstrated the excellent unpowered multi-function sensing performance of the microfabricated sensor, including

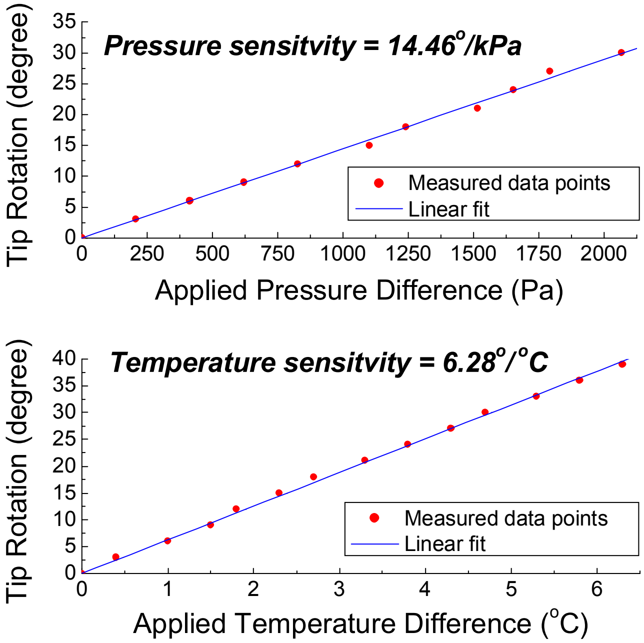

Fig. 6. Device testing results: (Top) Pressure testing; (Bottom) Temperature testing. Linear measurement data indicate linearly continuous pressure and temperature responses of the spiral-tube sensor.

short response time (< 1 sec), even without electronic acquisition. Depending on application requests, the sensing sensitivity can be enhanced using a more flexible spiral tube along with improved measurement resolutions using a more delicate optical system.

B. Sensor-Pair Characterization

Although sealed under different pressures (1 atm and 1.2 atm), the two spiral-tube sensors had exactly the same pressure responses in testing based on the facts that they were identical and operated in gauge pressure rather than absolute pressure sensing mechanism. The diversity was reflected on the measured temperature responses (Fig. 7) as expected. The measured temperature sensitivities in the two microsensors differed approximately 18% (6.28°/°C for the tube sealed under 1 atm and 7.44°/°C for the tube sealed under 1.2 atm), which was in good agreement with the 20% sealed pressure difference considering the ideal gas model. The discrepancy possibly caused by the large pressure difference between inside and outside of the spiral tube sealed under higher ambient pressure, so that radial deformation was no longer negligible and affected the pointing tip position. This characterization shows the difference of the temperature sensitivities was large enough to be used to decouple and retrieve the registered pressure and temperature variations, further confirms the feasibility of implementing this sensing configuration for both pressure and temperature monitoring in various environments.

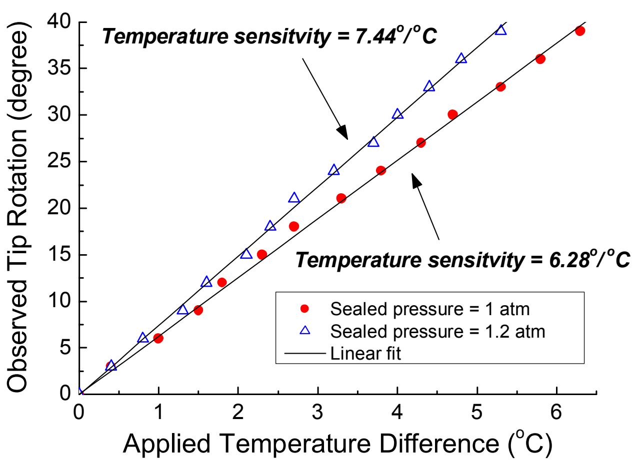

Fig. 7. Temperature testing result of the sensors in sensor-pair configuration.

VI. CONCLUSION

A micromechanical spiral-type parylene microsensor has been successfully designed, fabricated, and characterized. Its operation principle facilitates unpowered multi-function pressure and temperatures sensing out of the same device. By observing visible responses from the *in situ* rotational deformation of the spiral tube, sensing of the device completely obviates electronic acquisition and power consumption while acquiring adequate sensing performance. Testing results have shown highly linear and continuous pressure and temperature responses in single sensor characterizations. Moderate sensitivities as well as sub-kPa and sub-°C resolutions were obtained using the sensor. A modified sensor-pair configuration was also implemented to even decouple and retrieve both pressure and temperature readouts. These successful demonstrations verified the unpowered multi-function sensing capability of the microdevice toward practical pressure/temperature measurements in various systems, especially with long-term environmental monitoring applications.

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