Flexible Capacitor Sensors With Silver Nanowires

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Abstract. The flexible sensor can be applied in a wide range of fields like skin-clinging health monitor, surface antenna, AI, etc. The properties of the flexible sensor make it more capable and convenient. In this paper, a sandwich-structured flexible pressure sensor is made of spraying silver nanowires (AgNW) on the upper and downward polydimethylsiloxane (PDMS) layers. Silver nanowires are prepared by hydrothermal method, and combined with PDMS layers. The flexible pressure sensor is applied in medical areas such as portable heart rate monitor, heart rate detector, sound detector, etc. Also, it can be applied in areas like an artificial robot and other physical detector. The flexible pressure sensor made of silver nanowires and PDMS has better performance in sensitivity, flexibility, and transmittability.

1. Introduction
Rigid multi-electrode pressure sensors are well developed and have been applied in detection fields. However, the demerits of this kind of sensor are also obvious. It is hard and unable to bend, when the external force is applied to it. Its own rigid properties do not allow it to bend. The frame of the traditional pressure sensor is metal, and it is usually made of metal and part of it. Because hard metals have extremely poor stretchability, bending is almost impossible for traditional pressure sensors. Thus, the traditional rigid sensor is easily damaged by external forces and is not portable. Currently, people are focusing on the flexible pressure sensor due to its outstanding stretching ability. It is applied in health monitor systems [1], artificial intelligence [2-4], and other fields that need pressure sensor. Pressure sensors that are composed of silver nanowires performs better with better sensitivity and extensibility. Traditionally, researchers have used microstructured silicon molds to replicate thin films, but silicon molds are complicated and expensive to make. Manufacturing highly sensitive, low-cost sensors remains a huge challenge. Whereas in flexible pressure sensors everything is relatively inexpensive, the author prepared capacitive sensor electrodes with silver nanowires (AgNWs) as material and polydimethylsiloxane (PDMS) as dielectric layer. The capacitance change is converted to frequency by an oscillating circuit, and the signal is acquired directly by Keithley 2700. This method has the advantages of low power consumption, high sensitivity, accurate digital output and easy integration into measurement system. Keithley 2700 is a highly sensitive capture equipment, it has an accuracy of six and a half digits (22 digits), so it is possible to measure changes in capacitance at high frequency to achieve high-precision measurement.

The capacitance of the flexible sensor is calculated by the formula: \[ C = \varepsilon_0 \varepsilon_r d \] \( A \) is the area covered by two PDMS plates; \( d \) is the distance between the two PDMS layers which is equal to the thickness of the dielectric layer.
The significance of this experiment is to explore possible future applications of flexible pressure sensors through testing, making more sensors more portable, and helping humans to further develop in the medical and mechanical fields.

2. Experiment:
Figure 1 illustrates the structure of the pressure sensor. It is sandwich structures because it consists of two layers of PDMS sandwiched between a dielectric layer (it has functioned as a layer of air in order to ensure the sensor can make distance change between the other two layers), and a layer of AgNW is sprayed on the inside of the two layers of PDMS respectively.

2.1. Preparation of PDMS
PDMS is prepared using Sylgard 184 (Dow Corning) by mixing "base liquid" and "curing agent" at a mass ratio of 10:1. Stir the two liquids for ten minutes and put them in the refrigerator. After the bubbles disappear, the liquid mixture is spin-coated on the frosted surface glass at 500 revolutions per minute. Next, the film is exposed to 90°C for 15 minutes to form a cured PDMS, which is then peeled from the glass mold. The undulating patterns on the surface of the frosted glass are copied onto the PDMS(Figure 1).

The physical feature of this PDMS layer is it can bend to an outstanding rate. Because when an outer force is applied to the sensor, the curves on the outside layer can bend and become straight, it increases the strength of the surface which allows PDMS layer to become more stretchable.

2.2. Preparation of AgNWs
AgNWs are prepared by hydrothermal synthesis. 0.2g of polyvinylpyrrolidone (PVP), 0.002g of NaCl and 0.108g of AgNO3 are added to 6ml, 2ml, and 6ml of ethylene glycol solution and magnetically stirred until completely dissolved. The mixture is poured into a stainless steel autoclave lined with polytetrafluoroethylene, then kept at 120°C for 3 hours and then adjusted to 140°C for 1 hour to accelerate the growth of silver nanowires. After the mixture is cooled at room temperature, the silver nanowire mixture is centrifuged in acetone, ethanol and deionized water 3-5 times. Pour off the supernatant and collect the gray sediment at the bottom of the centrifuge tube. After removing the precipitate, add 100ml of ethanol to quickly obtain a stable AgNWs dispersion.[5-6]

2.3. Fabrication of flexible substrate electrode.
After fabricating the PDMS thin film, put it on a 120°C hotplate. Then spray the AgNWs uniformly on the PDMS thin film by the airbrush about 20cm. Wait until the AgNWs cool down and are stable. This
process is essential to ensure the bending ability of the flexible pressure sensor. The airbrush sprays the AgNW as net shape which ensures the sensor is more flexible and stretchable.

![Image of AgNWs](image1.png)

**Fig.2. Images of AgNWs:** (left) the solution of nano-silver particles; (right) SEM image of silver nanowires in 1 nm.

### 2.4. Combination

After every two layers of PDMS are combined with AgNW, silver glue is used to bond the silver wire to AgNW layer. The last one is three layers of PDMS. Because one side of PDMS is smooth, the surface adhesion is very strong. Finally, our flexible pressure sensor is completed.

The structural property makes the sensor flexible. When an external force is applied to the pressure sensor, the internal structure of the sensor can be extended, just like a retractable folding ladder. As long as the external force is received, the "folding ladder" will unfold, ensuring accuracy while increasing the surface area.

Caused by the nanosized effect, the AgNWs have prominent flexibility, electrical conductivity and consistency. Therefore, AgNWs are prior selections for flexible electrodes. Furthermore, the process of preparation of AgNWs in this experiment will greatly decline the fabrication cost.[7]

### 3. Result

The purpose of preparing the sensor in this paper is to apply it in practice, so further verification of the sensor is needed. Using the viscosity of the sensor, the author applied the prepared flexible pressure sensor to the throat to monitor the vibration of the muscles when the author uttered. As shown in the figure, the transmission test shows that the sensor has high sensitivity and resolution ability. When the author speaks different words or sentences, the sensors have different response signals Figure 3.

As you can see from Figure 3(a), within 30 seconds, the author’s heart beat 49 times. The heart rate of a normal person is 60-100 beats per minute. Comparing the data measured by us, it can be easily found that the data measured by the pressure sensor according to the pressure change caused by the pulse beat is relatively accurate.

In Figure 3(b), the change in capacitance is easily observed from 0-3s that can represent low-frequency vibration, and the frequency of 3-5s also becomes higher, which means high-frequency vibration.
In order to further study its repeatability, the author repeated "this is a flexible sensor" twice, each time with a different frequency, one high and one low. The test result shown in Figure 3(b) shows that the response curve obtained when the same text pronunciation is tested has a certain similarity. It can be seen that this micro-nano structured sensor provides an effective way of speech recognition, which is mainly due to the deformation of the epidermis and muscles around the throat during speech. Therefore, the flexible pressure sensor can be applied to the recovery of human vocal cord injury, trying to restore the speech ability by controlling the vibration of the throat muscle group of the patient. At the same time, this sensor is also expected to be used in the remote human-computer interaction interface.

Then the author applied continuous force to the flexible sensor and observed the change of capacitance. The author found that the greater the force received by the flexible pressure sensor, the greater its capacitance.

In Figure 4(a), applying wooden blocks of 14.87g, 17.24g and 19.76g to the flexible pressure sensor in sequence and adding them together, it is found that as the pressure increases, the capacitance also increases steadily from originally 15pF to 16.5pF, 17pF, and 17.5pF. When pressure is removed, the response value of the sensor can quickly return to the initial value, and the response time is less than 2s. It can be seen that the prepared micro-nano structure sensor has good stability and fast response time.

As shown in Figure 4(b), the sensor is pasted on a robotic arm to test the change in capacitance of the pressure sensor when the robotic arm grabbed an object. It can be clearly seen from the chart that the capacitance of the sensor has increased significantly during 1.75-2.75s.
4. Conclusion and outlook
Based on experiments and tests, it is demonstrated that the preparation method of the flexible pressure sensor composed of silver nanowires is not difficult and the cost is not high. The flexible sensor can be used to measure heartbeat rates, vocal vibration rate under different frequencies, capacitance change under different pressure, and capacitance change when applied on robotic arms. In the experiment, the heartbeat rate is 98 times per minute, the vocal vibration rate is also different under frequency, the capacitance increases with increasing force, the bounce of capacitance when the sensor was applied to a constant force.

The results are still immature in the field of capacitive flexible pressure sensor research, and there are still many deficiencies in theoretical research, device performance and application field exploration, and further in-depth theoretical research and reliable experimental testing are needed. Due to the limited time, there are still imperfections in this paper, and there are many aspects that can be studied in depth. The future research can be divided into the following aspects:

1. It is necessary to further study the reliable theoretical model of the flexible pressure sensor, so that it has better versatility and higher accuracy, and is used to improve and optimize the performance of the sensor.
2. Study the influence of the concentration of silver nanowires on the sensitivity of the capacitive sensor, and optimize the concentration of silver nanowires to make the capacitive pressure sensor have higher transparency and higher sensitivity.
3. Build a more complete test platform to test the actual application effects of flexible sensors, so that sensor applications can be more practical.
4. Study the influence of the micro-nano structure of the dielectric layer film on the performance of the capacitive sensor, and study the influence of the dielectric layer of different polymer materials on the sensor performance. Discuss the influence of the different thicknesses of the dielectric layer on the sensor.

Acknowledgement
First of all, I would like to thank Dr. Yiding Gu from Laboratory of Advanced Photonic Materials and Devices. He led me to complete this experiment and understand the principle of capacitive pressure sensor and the entire preparation process. I also thank the Professors from the lab, they provided me with the experimental equipment and guidance on the way of thinking of the paper.

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