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The Manufacture and Mechanical Analysis of the PVDF Flexible Sensors

[1] Hongbin ZHU, [1,2] Yanjun LU, [3] Xu LIU, [2] Yingtian YU
[1] Xi’an University of Technology,
5 South Jinhua Road, Xi'an Shaanxi, 710048, China
[2] Michigan State University,
428 South Shaw Lane, East Lansing, MI, 48824, USA
[3] Xi’an Aeronautical University,
259 West 2nd Ring, Xi'an Shaanxi, 710077, China
E-mail: yanjunlu@xaut.edu.cn

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Abstract: Polyvinylidene fluoride (PVDF) is a widely used sensing material with piezoelectricity property. Applying microelectronic technology to this material could result in multifunctional sensing unit. Based on the previous researches, a manufacturing process and flexible structure are proposed to manufacture the PVDF film and the PVDF flexible sensor using stretchable electronic technology. The sensor is designed to be paved on the surface of airfoil to monitor the structural behaviors. Two systems are compared, one with a polydimethylsiloxane (PDMS) layer and the other without. The finite element results show that the Au electrodes films are harder to be destructed for the system with PDMS, because the PVDF flexible sensor can realize the strain-isolation, therefore the resistance to destruction of the sensors could be improved. However, the deformation of duralumin is increased, so the substrate that the flexible sensor paves on will undertake a majority portion of stresses and strains, and a substrate with reasonable stiffness will contribute to the structure integrity. *Copyright © 2013 IFSA.*

Keywords: Manufacture, Flexible sensor, Flexible electronics, Finite element method, Polyvinylidene fluoride.

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1. Introduction

The previous researches have demonstrated that the PVDF film possesses many advantages, such as the suppleness, light weight, high mechanical strength, wide frequency range (0.1-100 MHz), quick responsiveness and strong corrosion resistance [1-3]. Due to the performance of PVDF thin film, applying it to the flexible sensors could track the fold status of airfoils. The flexible sensor, which possesses a stretchable substrate is a special application of flexible electronics. It could adapt to rugged surfaces and different external environments, as a result the application of flexible sensor is extended. Recently, there are various applications of flexible sensors, such as force, pressure, temperature, strain, stress, contact sensors [4-10], etc. The flexible sensor can be used to measure the mechanical parameters, monitor the health state of a system, react to the joint behavior of robotics, or be implanted into human body to detect the abnormal cells [1, 11-18], etc.

According to the previous manufacturing process of PVDF film and flexible sensor [19-22], a PVDF flexible sensor is designed and manufacturing process is presented in this paper. This newly designed flexible sensor will be paved on the surface or be embedded into the inner structure of aircraft to monitor the health state of airfoil structure. In order to understand the characteristics of the designed PVDF flexible sensor, it is assumed that the sensor is subject to the conditions of bending, stretching and twisting, and two structures have been compared, one with PDMS layer and the other without. The FEM results show that the Au electrodes are fragile in the structure without PDMS layer, because the structure with PDMS layer reduces the stress and strain of the Au electrodes. The result suggests that the soft PDMS layer can reduce the strain and stress that are transferred from the duralumin to the Au electrodes. This design can prevent the proposed flexible sensor from being destructed in various conditions.

2. The Structural Design and Manufacture of the PVDF Flexible Sensor

There are two methods to manufacture the PVDF flexible sensor, one is peeling the sensors that have been accomplished from a hard substrate to a stretchable substrate, the other way is making an induction device by micro-electro mechanical systems technology and finishing the sensor on a stretchable substrate directly.

The first approach is adopted in the experiment to create a high quality PVDF film. From past experiments, we have found that a 15 % mass fraction PVDF powder and 85 % dimethylformamide solution have a high film-forming capability. Fig. 1 shows the cross section structure of the PVDF flexible sensor.

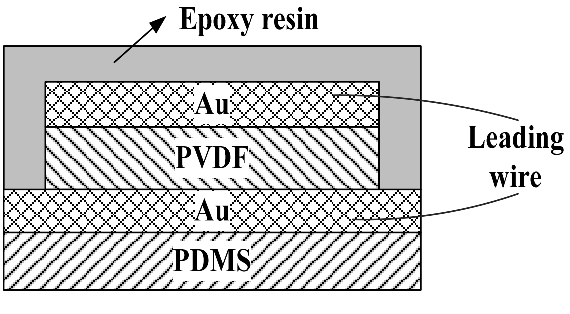


Fig. 1. The schematic diagram of designed flexible PVDF sensor structure.

During the manufacturing of the flexible sensor, the PVDF film is made on silicon wafer, and Au is deposited on the surface of PVDF film, thus the electrode layer is achieved. And then the Ag wire is connected with the electrode through conductive adhesive. Finally the epoxy glue is used to reinforce the surface of connection point, and the sensor is encapsulated with epoxy resin.

2.1. The Manufacturing Process of PVDF Film

a). A certain amount of PVDF powder was weighed and dissolved into dimethylformamide solvent slowly. One must ensure the mass fraction of PVDF is 15 %.

b). The solution in step (a) should be stirred more than 2 hours by magnetic stirrer rapidly at room temperature, then let it remain undisturbed for over 12 hours, the PVDF would be dissolved completely.

c). The silicon wafer is adsorbed to the turnplate of spin coater, and a reasonable revolving speed is chosen so that the silicon wafer will not slip out.

d). The PVDF solution is smeared on the silicon wafer and rotated for 1 minute with the rotating speed of 900 r/min, after that, the film is heated for 10 minutes at 90°C.

e). Step (d) is repeated on the same silicon wafer and the PVDF film is heated for 12 hours at 120°C. The PVDF film on the silicon wafer with a few micrometers thickness is obtained by this method.

2.2. The Manufacturing Process of the PVDF Flexible Sensor

a). The silicon chip is cut into dimension of 2 cm wide and 3 cm long, and a silica layer with 600 nm thickness is deposited on silicon wafer chemically. The silica layer is a sacrificial layer, which means this layer will be etched when all the devices are finished, so the device could be separated from the silicon substrate and a sensor with a stretchable base can be formed.

b). A PDMS layer is applied on the silica that is considered as a flexible substrate.

c). A 300 nm thick Au layer as the substratum electrode is deposited on the top surface of PDMS by electron beam deposition. Fig. 2 shows the Au spray layer on PVDF film.

Fig. 2. The substratum Au electrode on PDMS film.

d). About 2 μm thick PVDF film is obtained on the substratum electrode (the manufacturing process can be referred to section 2.1.).

e). A 300 nm thick Au layer is electron sedimentated as the superstratum electrode on PVDF top surface, in order to avoid a capacitance structure to be formed between superstratum and substratum electrodes, the size of electrodes should not equal each other.

f). The specimen is immersed into hydrofluoric acid (HF) with the concentration of 12.5 % about 5 minutes, and then most of silica is etched.

g). The etched specimen is peeled from the silicon by PDMS, and is transfer printed onto another PDMS layer, which has been radiated for 3 minutes with a UV light before.

h). The wires are bonded to electrodes by conducting resin, then epoxy glue is used to strengthen the surface, and the sensor is encapsulated with epoxy resin finally.

Fig. 3 shows the manufacturing process of the flexible PVDF sensor. In order to obtain a better voltage signal, the thickness of the PVDF film should be increased. However, the film cannot be too thick, and the number of smearing should not exceed three times, otherwise the smeared solution will dissolve the already dried film. The PVDF film is very soft and the melting point is 160 °C, so the high temperature depositing Au particle will cause a deformation in the surface, and the Au electrode layer tends to be broken because of a rough Au surface.

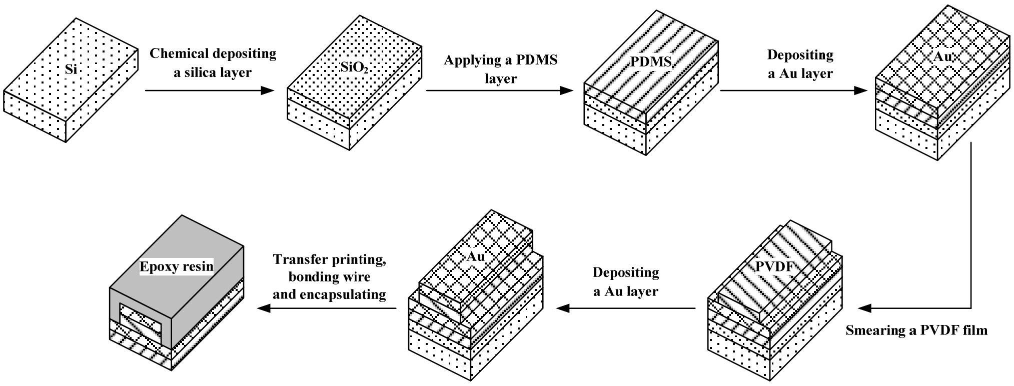
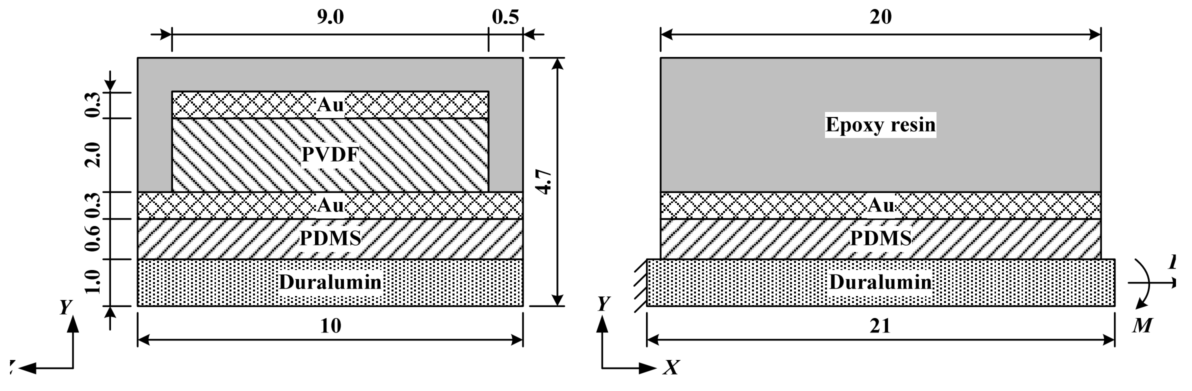


Fig. 3. Manufacturing process of the flexible PVDF sensor.

3. Simulation and Results

In this section, three conditions have been discussed, bending, twisting and stretching. The structure designed is shown in Fig. 4. The unit is micrometer in Fig. 4, and the physical parameters are shown in Table 1. E is the elastic modulus, v is Poisson ratio, C is the elastic stiffness tensor, e is piezoelectric constant, κ is the permittivity tensor, and the subscript means tensor direction [23-28]. In Fig. 4, the coordinate axis X, Y and Z represent the direction of length, thickness and width; M and D are applied moment and displacement on the right surface of duralumin; the left surface of duralumin is fixed. In order to demonstrate the superior strain-isolation effect of the structure with a flexible layer, two structures have been compared. Fig. 4 shows the structure with a PDMS layer, and the other structure without PDMS layer is not shown in Fig. 4.



(a)

(b)

Fig. 4. The simulation structure and geometry size. (a): The view of *Y-Z* plane; (b): The view of *X-Y* plane.

3.1. Bending

A negative moment is applied to the system without PDMS layer. When the moment reaches -5×10^{-4} N·m, the stress in substratum Au electrode is approaching its yield strength, at the same time, the duralumin is still within elastic limit. While increasing the moment to -8.5×10^{-4} N·m, the stress in duralumin is close to its yield strength, but the Au electrode fails. As result the Au will be destructed before the stress in duralumin reaches its allowable stress. On the other hand, if the system has a PDMS layer, the stress in Au electrode is much lower than without PDMS layer. When the applied moment is -5×10^{-4} N·m, the maximum stress in substratum Au is reduced to one third of the value without PDMS layer. When increase the moment to -7.2×10^{-4} N·m, the stress in duralumin reaches the yield strength, but the Au electrodes do not fail, which means the adaptive capability of flexible system is much higher than the system without a PDMS layer. Table 2 shows the maximum stress of the Au electrodes and duralumin for the applied moments, because the PVDF, PDMS and encapsulation layer are far away from destruction, so they are not discussed here. Fig. 5 and Fig. 6 show the correlation curves for the two structures, the curves with ‘*’ are for the structure without PDMS layer, and the curves with ‘○’ are for the structure with PDMS layer, the chosen nodes are along the central axis of the geometry from left end to right end, which is parallel to X axis. The stress and deflection of superstratum and substratum Au film are presented. Fig. 5 shows the results when negative moments are applied to the two structures; Fig. 6 shows the results when positive moments are applied to the two structures; (a)-(d) are with the same moment magnitudes; (e)-(h) are under the condition that the duralumin stress reaches its yield strength.

3.2. Stretching and Compression

A displacement is applied on the right surface of duralumin, the results are obtained by FEM. Table 3 shows the maximum stress of Au electrodes and duralumin before the destruction of duralumin. The results show that the structure with PDMS flexible layer could reduce the stress significantly. Fig. 7 shows the displacement of Au electrodes in Y direction. The PDMS flexible layer undertakes most of the deformation, so the displacement of Au electrodes approaches zero. The maximum displacement of Au films is 0.611 nm for D=-31 nm; the maximum displacement of Au films is -0.609 nm for D=+31 nm. The results show that the flexible layer attenuates the deformation of Au films.

3.3. Twisting

Due to the similarity of displacements and stress for both positive and negative torque, as well as the distribution of stress in the same layer being uniform, therefore only negative torque is investigated. By applying a negative torque to the right side of the duralumin, the maximum stress and displacement are obtained for different layers, which are shown in Table 4 and Table 5.

The torque loading capacity of the structure with PDMS layer is lower than the structure without the PDMS layer. The reason is that the deformation of duralumin increases while it decreases in Au electrodes. As a result, the duralumin will be destructed before the Au electrodes do in the system with PDMS layer, because the substratum Au electrode becomes harder to be broken in this system. Therefore the performance of the system with PDMS layer will be promoted by lowering the stiffness of the substrate material.

Table 1. Physical parameters of the materials.

Material	Physical parameters
Duralumin	E=70 GPa, ν=0.3, yield strength=450 MPa
PDMS	E=2 MPa, ν=0.48
Au	E=79 GPa, ν=0.42, yield strength=220 MPa
PVDF	C_{11}=3.8 GPa, C_{12}=1.9 GPa, C_{13}=1.0 GPa, C_{33}=1.2 GPa, C_{44}=0.7 GPa, C_{66}=0.9 GPa, e_{15}=0, e_{31}=0.024 C/m^2, e_{33}=-0.027 C/m^2, κ_1=7.4κ_0, κ_3=7.6κ_0, κ_0=8.85×10^{-12} C/m^2
Epoxy resin	E=1 GPa, ν=0.38

Table 2. The maximum stress in Au electrodes and duralumin.

Structure	Without PDMS layer		With PDMS layer	
Applied moment, (N·m)	-5×10^{-4}	-8.5×10^{-4}	-5×10^{-4}	-7.2×10^{-4}
Maximum stress, (MPa) (Superstratum Au film)	58.0	98.6	60.0	86.4
Maximum stress, (MPa) (Substratum Au film)	210.2	357.4	66.9	96.4
Maximum stress, (MPa) (Duralumin layer)	258.2	438.9	307.5	442.8
	The yield strength of duralumin is 450 MPa, the yield strength of Au is 220 MPa.			

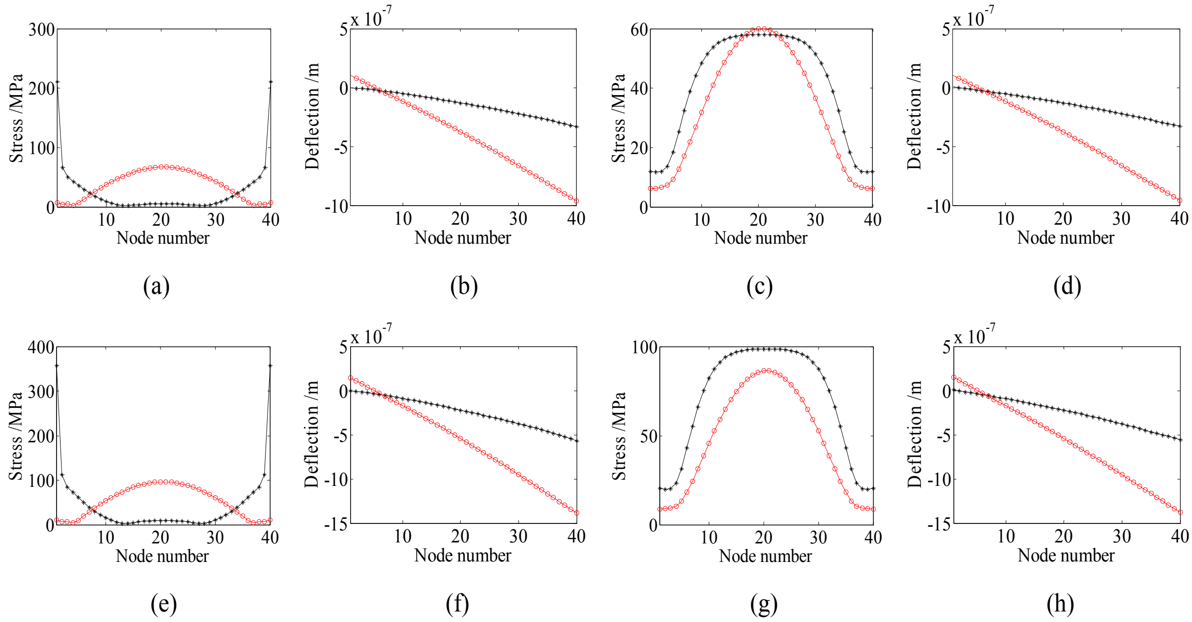


Fig. 5. The results of comparison between the structures with and without PDMS layer for negative moment, ‘*’– without PDMS layer, ‘○’–with PDMS layer. (a) Stress curves of substratum Au electrode for $M=-0.5\times10^{-3}$ N·m; (b) Deflection curves of substratum Au electrode for $M=-0.5\times10^{-3}$ N·m; (c) Stress curves of superstratum Au electrode for $M=-0.5\times10^{-3}$ N·m; (d) Deflection curves of superstratum Au electrode for $M=-0.5\times10^{-3}$ N·m; (e) Stress curves of substratum Au electrode when the stress of duralumin reaches its yield strength; (f) Deflection curves of substratum Au electrode when the stress of duralumin reaches its yield strength; (g) Stress curves of superstratum Au electrode when the stress of duralumin reaches its yield strength; (h) Deflection curves of superstratum Au electrode when the stress of duralumin reaches its yield strength.

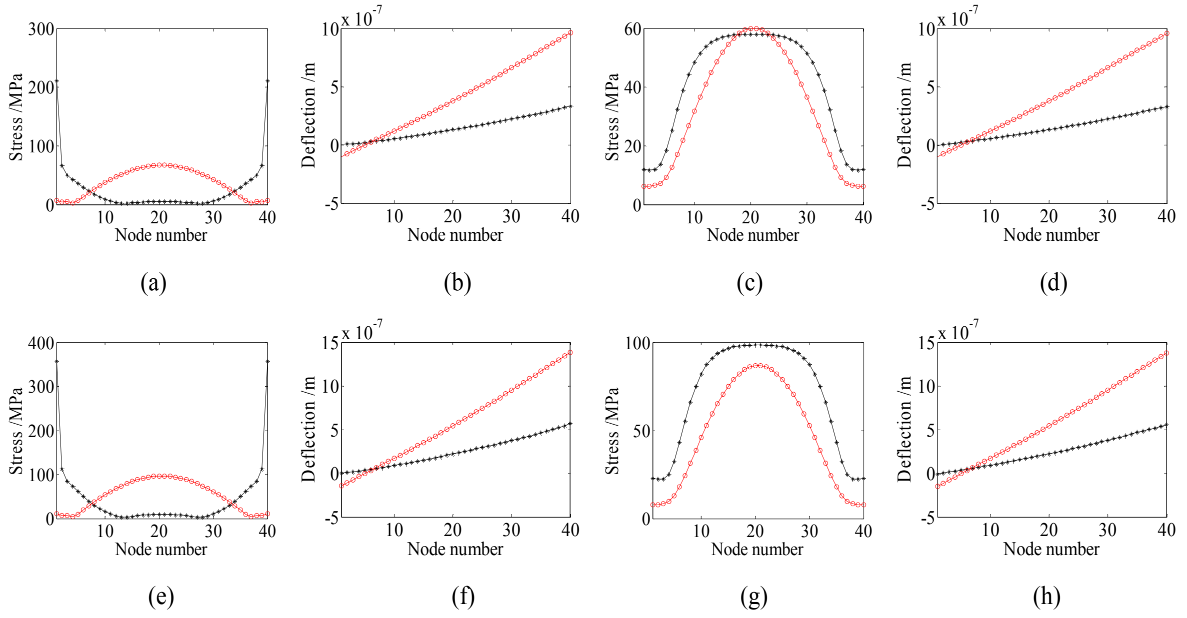
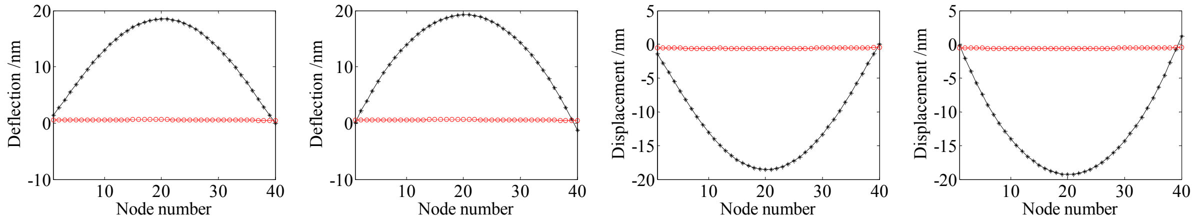


Fig. 6. The results of comparison between the structures with and without PDMS layer for positive moment, ‘*’– without PDMS layer, ‘○’–with PDMS layer. (a) Stress curves of substratum Au electrode for $M=+0.5\times10^{-3}$ N·m; (b) Deflection curves of substratum Au electrode for $M=+0.5\times10^{-3}$ N·m; (c) Stress curves of superstratum Au electrode for $M=+0.5\times10^{-3}$ N·m; (d) Deflection curves of superstratum Au electrode for $M=+0.5\times10^{-3}$ N·m; (e) Stress curves of substratum Au electrode when the stress of duralumin reaches its yield strength; (f) Deflection curves of substratum Au electrode when the stress of duralumin reaches its yield strength; (g) Stress curves of superstratum Au electrode when the stress of duralumin reaches its yield strength; (h) Deflection curves of superstratum Au electrode when the stress of duralumin reaches its yield strength.

Table 3. The maximum stress of Au electrodes and duralumin.

Structure	Without PDMS layer				With PDMS layer			
Applied displacement (nm)	-45	-31	45	31	-45	-31	45	31
Maximum stress (MPa) (Superstratum Au film)	21.6	14.9	215.9	14.9	0.1458	0.0998	0.1504	0.1043
Maximum stress (MPa) (Substratum Au film)	313.4	215.9	313.5	215.9	0.5264	0.3631	0.5235	0.3062
Maximum stress (MPa) (Duralumin layer)	443.1	305.2	443.1	305.2	208.5	143.6	208.5	143.6
	The yield strength of duralumin is 450 MPa, the yield strength of Au is 220 MPa.							



(a) (b) (c) (d)

Fig. 7. The comparison of the displacements of the structure with and without PDMS layer, '*'– without PDMS layer, '○'–with PDMS layer. (a) Displacement curves of substratum Au electrode for D=-3.1×10^{-8} m; (b) Displacement curves of superstratum Au electrode for D=-3.1×10^{-8} m; (c) Displacement curves of substratum Au electrode for D=+3.1×10^{-8} m; (d) Displacement curves of superstratum Au electrode for D=+3.1×10^{-8} m.

Table 4. The maximum stress of Au electrodes and duralumin.

Structure	Without PDMS layer		With PDMS layer
Applied torque (N·m)	-1.2×10^{-3}	-1.55×10^{-3}	-0.82×10^{-3}
Maximum stress (MPa) (Superstratum Au film)	166.9	219.5	0.9898
Maximum stress (MPa) (Substratum Au film)	218.5	282.3	101.9
Maximum stress (MPa) (Duralumin layer)	344.9	445.5	444.2
	The yield strength of duralumin is 450 MPa, the yield strength of Au is 220 MPa.		

Table 5. The maximum displacement of Au electrodes and duralumin.

Structure	Without PDMS layer		With PDMS layer
Applied torque (N·m)	-1.2×10^{-3}	-1.55×10^{-3}	-0.82×10^{-3}
Maximum displacement (nm) (Superstratum Au film)	151.7	195.9	258.1
Maximum displacement (nm) (Substratum Au film)	190.3	245.8	290.6
Maximum displacement (nm) (Duralumin layer)	193.7	250.2	473.8

4. Conclusion

The PVDF flexible design contributes to the sensor's adaptability, which prevents the components from being destructed. The comparison results of the two structures with and without PDMS layer show that stresses in Au electrodes decrease while the corresponding stresses in duralumin increase. This phenomenon that is caused by the flexible layer prevents strain and stress from being transferred from duralumin to the sensor, so the duralumin undertakes a significant portion of the external load. It is shown in section 3.3 that duralumin will be broken with a lower torque in flexible structure. Thus a suitable PDMS thickness and substrate stiffness are important to the system. Overall, the strain isolation of the flexible sensor exceeds the system without a PDMS layer, the circuit of the sensor can be protected. The results shown in this paper will provide guidance to the design and manufacture of the flexible sensors. The thickness of PDMS layer and substrate stiffness may be altered under different working conditions, and the reasonability and feasibility of the flexible structure should be further researched.

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