KIRIGAMI CROSS-SHAPED 3D BUCKLING ACTIVE SENSOR FOR DETECTING STRETCHING AND BENDING

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ABSTRACT

Stretchable and movable 3D structure is a great choice for sensing stretching and bending. This paper reports a novel cross-shaped 3D buckling strain sensor based on polydimethylsiloxane (PDMS) substrate for detecting stretching and bending. Using pre-stretched PDMS, cross-shaped Polyimide (PI) film with conductive silver paint on its top surface as a 2D precursor can pop up as a dynamic 3D structure and possesses capacitive effect and triboelectric effect under different stretching and bending, which can detect stretching directions, strain value, bending axis direction and radius of curvature simultaneously, showing great potential in human and robot applications.

KEYWORDS

Kirigami cross-shaped 3D structure, active sensor, stretching detecting, bending detecting, triboelectric effect.

INTRODUCTION

Sensors for detecting stretching and bending has great application value in detecting joint movement and motion for human and robots [1-3]. Various materials and structures have been researched for this kinds of strain sensor such as carbon nanotube (CNT) based thin conductive film [4,5], porous polymer [6,7] and microstructure array [8,9]. Among them, stretchable and movable 3D structure which responses to stretching and bending sensitively is a good candidate.

Assembly of kirigami 3D structure achieved by releasing a multilayered 2D precursor on a pre-stretched elastomer has attracted more and more attention due to its simple fabrication process and structural stability [10]. These kirigami 3D structure can be utilized in many aspects such as energy harvesting [11], tunable optical transmission window [12] and 3D mciro-frameworks for guided growth of biological systems [13]. The stretchable and movable 3D structure has the ability to response sensitively to external mechanical stimuli such as stretching and bending [14]. Besides, assembling from 2D to 3D means that 2D manufacture technology is also applicable, which indicates that adding various conductive materials onto 3D structure is feasible [15].

In this work, we design a kirigami cross-shaped 3D structure and successfully introduce the capacitive effect and triboelectric effect into the structure with flexible electrodes on it. The stretchable CNT-PDMS based electrode is used as the bottom electrode and flexible silver conductive paint is used as the top electrodes. By detecting changes of the capacitance and the triboelectric signals, the sensor is able to distinguish different tensile strength and bending.

MODELING AND EXPERIMENTAL

Working principle

The schematic of the cross-shaped 3D buckling active sensor is shown in Figure 1a. The basic working mechanism is based on capacitive effect and triboelectric effect triggered by stretching or bending. The 3D buckling arms with electrodes on them deform and recover to the flat state when the substrate is under stretching or bending. As shown in Figure 1b, when the sensor gets small tensile strength, the arms flatten and the distance between the arms and the soft substrate decreases but still without touch happened on the interface. In this stage, the capacitance increases with the distance of air gap decreases. That can be simplify as a classic capacitor model. Considering the capacitance formula

$$c = \frac{\varepsilon S}{d} \qquad (1)$$

Where c , ε , S , d represent capacitance, dielectric constant, area and distance, respectively. Thus, the whole capacitance of the sensor system can be subscribed as

$$\frac{1}{c_{arm}} = \frac{1}{c_{air}} + \frac{1}{c_{PDMS}} \qquad (2)$$

$$c_{arm} = \frac{\varepsilon_{air}\varepsilon_{PDMS}S}{\bar{d}_{air}\varepsilon_{PDMS} + d_{PDMS}\varepsilon_{air}} \qquad (3)$$

Where ε_{air} and ε_{PDMS} represent the absolute dielectric constant of air and PDMS, respectively. $\bar{d}_{air}$ and d_{PDMS} represent the equivalent distance of air gap and thickness of PDMS, respectively. S is the area of the capacitor.

When the sensor gets large tensile strength, the arms contact with the PDMS and as shown in Figure 1c and then become electrically charged on the surface because of triboelectric effect. In this stage, the buckling PI and the substrate PDMS work together as two charges generation surface and the air among them enables the PI arms and PDMS to contact and separate. Through the electrostatic induction, the conductive electrodes can provide mobile charges and produce a high electric signal. As for bending, the sensor also shows triboelectric effect and produces triboelectric signals.

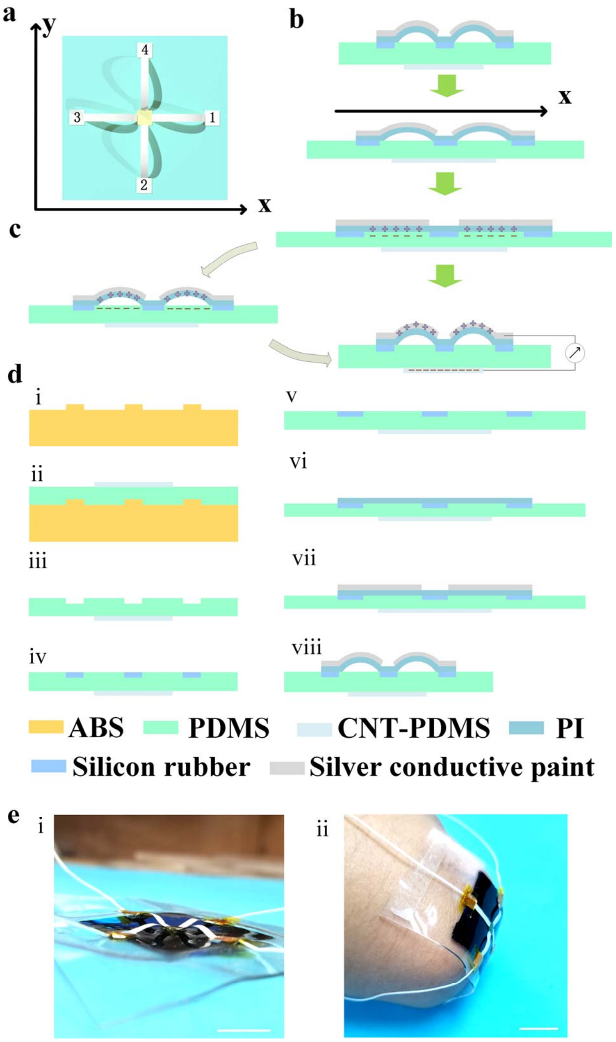

Figure. 1: a. vertical view of the sensor. b. Capacitive effect of the sensor under small stretching strain. c. Triboelectric effect of the sensor under large strain. d. Cross section schematic of the fabrication process. e. Practical photos of the sensor. Scale bar: 1cm.

Fabrication

The fabrication process is shown in Figure 1d. Firstly, an Acrylonitrile Butadiene Styrene (ABS) based 3D mold is printed by 3D printing. Then pour PDMS solution (mass ratio of pre-polymer to curing agent is 20:1) onto the mold, and heat it until curing of the polymer. Next, pour conductive CNT-PDMS solution onto the surface of PDMS to form a stretchable and flexible electrode. After that, remove the ABS mold and gluing at the cavities, stretch PDMS biaxially by 25%. The cross-shaped PI is fabricated by laser cutting. Spin-coat conductive silver paint onto one surface of cross-shaped PI film as an electrode layer and then fix the cross-shaped PI film onto the PDMS with five bonding sites aiming glued sites. Heat at 80 ˚C for about two hours. Finally, release the PDMS and the cross-shaped 2D precursor pops up as a dynamic and movable 3D structure.

Experimental setup

We use an experimental setup consisting of a home-made stretching plane, an oscilloscope and a probe stage. The output voltage was measured via a digital oscilloscope (Agilent DSO-X 2014A) using a 100 MΩ probe (HP9258). The capacitance was measured via a probe stage (HP4192A LF impedance analyzer).

RESULTS

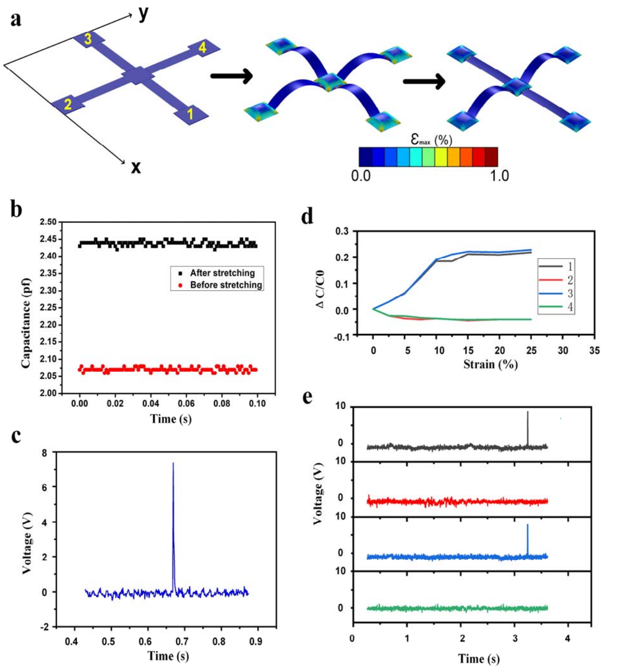

Figure 2: a. Dynamic change of the cross-shaped 3D structure by FEA. b. Capacitance changing under 15% stretching strain. c. Triboelectric output voltage pulse appearing at 25% stretching strain along the x axial. d. Capacitance changes of four arms. e. Triboelectric outputs of four arms.

Figure 2a is the finite element simulation results of the sensor changes from a 2D pattern to a 3D structure after releasing and deforms under a stretching along the x axial. The arms 1 and 3 flatten while 2 and 4 are still holding the bending state. From Figure 2b, the capacitance between arm 1 and the bottom electrode (CNT-PDMS) is about 2.06 pf at the initial state and increases to about 2.45 pf after stretching 15%. When stretching strain increases up to 25%, the triboelectric output signal is produced by contact and separate of PI layer and PDMS layer as shown in Figure 2c. The triboelectric signal appearance means that a large tensile strain (>25%) is applying onto the sensor, if continue stretching, the sensor may get physically damages. The Figure 2d and e show the capacitance changes and triboelectric outputs of four arms. The signal of capacitance and triboelectric output voltage of arm 1,3 and 2, 4 can be obviously distinguished and indicate the stretching strain along the x axial.

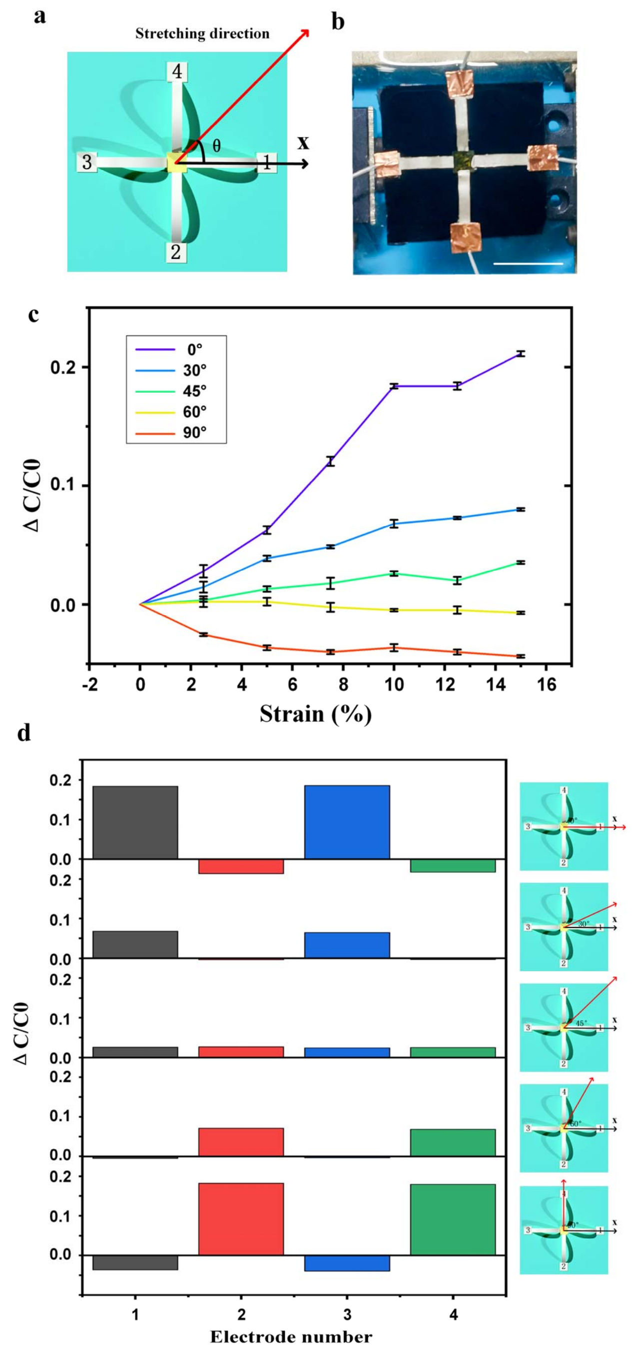

Figure 3: a. Definition of stretching direction. b. The practical testing photo. Scale bar: 1cm. c. Capacitance changing between electrode 1 and CNT-PDMS related to strain and stretching direction angle. d. Relationship between four capacitance changings (between electrodes 1 to 4 and CNT-PDMS) and stretching direction.

In Figure 3, the sensor with a dynamic and movable 3D structure shows great abilities of detecting stretching. The definition of stretching direction is shown in Figure 3a and Figure 3b is the practical testing photo of the sensor on a stretching plane. The capacitance changes as the stretching direction changes. The angle of the stretching direction has a negative effect on the sensitivity of increasing capacitance under increasing strain. When the angle of the is larger than 60°, the more strain leads to the less capacitance. This can be attributed to decreasing strain component along the x axial with the increasing angle of stretching direction. Figure 3d shows that four electrodes work together to detect the stretching direction.

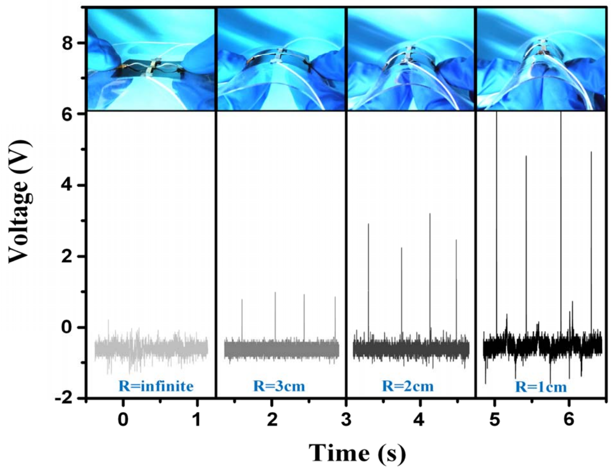

Figure 4: Triboelectric output voltages of the right electrode with different radius of curvatures (R). The output voltage increases as the R decreases.

In Figure 4, the less the bending radius of curvature, the higher triboelectric output voltage the sensor produces, which means it can detect the bending radius of curvature. The triboelectric output voltage is almost zero when the radius of curvature is infinite and the PDMS is not stretched at this state. While the radius of curvature is 3cm, 2cm and 1cm, the average output voltage is about 1V, 2.8V and 5.1V, respectively. In the bending process, the upper surface of the PDMS substrate is stretched and support a tensile strain for the 3D structure. The larger bending radius of curvature leads to higher average velocity of contact and separation, which produces higher output voltage.

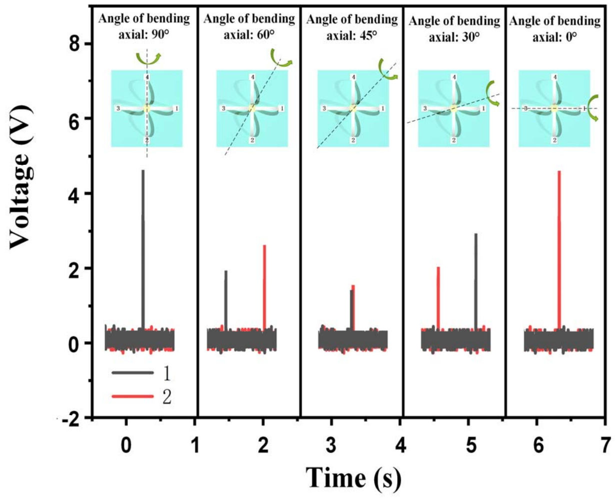

Figure 5: Relationship between direction of bending axis and output voltage of electrode 1 and 2. Angle of bending axial varies from 90°to 0°.

Besides, as shown in Figure 5, the output voltages of arms also vary with different direction of the bending axial.

When the bending axial changes from y axial to x axial, the voltage of arm 2 changes from zero to about 5V while the arm 1 has an opposite trend. Meanwhile, the two signals have time delay because of the different contacting and separating time caused by different angles of the bending axial.

CONCLUSIONS

In summary, we design and fabricate a novel kirigami cross-shaped 3D buckling active sensor for detecting stretching and bending. The cross-shaped PI is popped up by releasing the pre-stretched PDMS to form a stretchable and movable 3D structure bonding on PDMS. Due to capacitance effect under different tensile strain, this 3D sensor can detect stretching strain and stretching direction. With contact and separation of PI and PDMS, the active sensor possesses triboelectric effect which can detect large tensile strain, bending axis direction and radius of curvature simultaneously from output voltage signals. This kirigami cross-shaped 3D buckling active sensor is meaningful to apply into human and robots' motion and joint movement.

ACKNOWLEDGEMENTS

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CONTAC

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