Piezoresistive Sensor Based on High Performance Flexible Pressure Sensitive Film Material

Ruixian Zhang
School of Microelectronics
Southern University of Scince and Technology
Shenzhen, China
11910603@mail.sustech.edu.cn

Yuxuan Zhou
School of Microelectronics
Southern University of Scince and Technology
Shenzhen, China
11911007@mail.sustech.edu.cn

Bihong Zhang
School of Microelectronics
Southern University of Scince and Technology
Shenzhen, China
11910609@mail.sustech.edu.cn

Shuo Feng
School of Microelectronics
Southern University of Scince and Technology
Shenzhen, China
11911736@mail.sustech.edu.cn

***Abstract*—Presure Sensor is of vital importance in daily life, from macro scale to micro scale. Traditional mechanical pressure sensors are (a) rigid materials such as metal conductors or semiconductors; and (b) the flexible pressure sensor made of polymer piezoelectric material and conductive polymer composite materials. Our research is focused on the flexible pressure sensor, which has a wider application value and gets more attention with the maturity of micro-nano processing technology.**

***Index Terms*—Flexible thin film pressure sensors, microstructure, wearable electronic devices**

I. Introduction

This report focuses on the preparation of high-performance flexible thin film pressure sensor in the following aspects: Firstly, explore the process flow of screen printing to study the fabrication of periodic surface micro-structure sensitive layer by screen printing process. Secondly, analysis the influence of different factors on the performance of the flexible film pressure sensor. Last part will explore the application of the flexible thin film pressure sensor in the field of wearable sensor and electronic skin, and propose more extensive application scenarios according to the characteristics of the sensor.

II. Background

A. Significance of the Topic

At present, sensors based on conductive polymer composite materials have gradually developed mature, and there are quite a number of new structures and new materials of flexible pressure sensor development, and these new flexible pressure sensors have become the core devices of wearable electronic devices and electronic skin.

In the biomedical field, there is often a demand for large-area pressure signal acquisition. Compared with traditional sensors, the thin-film flexible pressure sensor has natural advantages in large-area preparation, integration and signal exploration. For example, in the treatment of flat feet and abnormal walking posture, there is often a need to obtain the pressure distribution and the change of that of the patient's foot. It is also necessary to check whether the pressure between the left and right buttocks and the stool is consistent in the treatment of spinal dysplasia and improper sitting posture. These scenarios have high requirements for flexible array pressure sensor systems that can detect large area pressure distribution in real time and measure large range pressure.

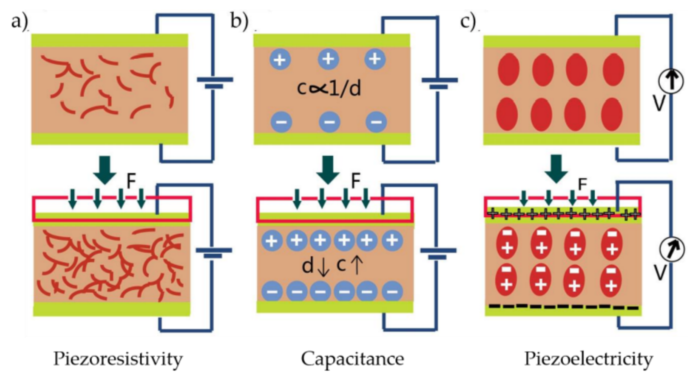


Fig. 1. Schematic illustration of three common transduction mechanisms and representative devices:(a) piezoresistivity; (b) capacitance; and (c) piezoelectricity.

B. Classification of Flexible Pressure Sensors

Pressure sensors is a device which can convert the pressure signal to electrical signal. Schematic illustration of three common transduction mechanisms and representative devices are: piezoresistivity, capacitance and piezoelectricity, which is shown in fig. 1.

In our design, we will make use of the property of piezoresistivity.

Identify applicable funding agency here. If none, delete this.

C. Performance Evaluation Criteria

There are several indicators to quantify the performance of the pressure sensors. They are **Linearity**, **Sensitivity**, **Response Time**, **Measuring Range**, **Durability**, etc.

- **Linearity**
  In practical application, the electrical signals of the pressure sensor should change monotonously with the pressure signal. However, most flexible sensors using polymer materials are nonlinear elastic material. To deal with those which do not have strict linearity of pressure sensor, the sensitivity is usually defined as: within the scope of a certain pressure, electrical signals of the ratio of relative variation and pressure variation have positive correlation.
- **Sensitivity**
  In recent studies, the Sensitivity S of flexible pressure sensors is mostly given by the following formulas

$$S_R = \frac{\Delta R/R_0}{\Delta P} = \frac{(R - R_0)/R_0}{\Delta P} \tag{1}$$

$$S_G = \frac{\Delta G/G_0}{\Delta P} = \frac{(G - G_0)/G_0}{\Delta P} \tag{2}$$

$$S_C = \frac{\Delta C/C_0}{\Delta P} = \frac{(C - C_0)/C_0}{\Delta P} \tag{3}$$

  S_R, S_G and S_C are the sensitivity of resistive, conductance and capacitive flexible pressure sensors respectively, and R_0, G_0 and C_0 are the initial resistance, initial conductance and initial capacitance of these three sensors respectively. Δ P is the pressure applied to the sensor, and the unit of sensitivity is generally kPa^{-1}. When the absolute sensitivity of the sensor is greater than 1 kPa^{-1}, the sensor is considered to have excellent sensitivity.
- **Response Time**
  The response time of the new flexible pressure sensor is the time when the pressure is applied to the sensor and the signal changes to the electrical signal corresponding to the pressure. Normally, the flexible sensors have the response time less than 100 ms.
- **Durability**
  Measurement range refers to the range between the minimum pressure that the sensor can sense and the maximum pressure that can generate signal response. Durability is generally characterized by the number of dynamic cycle measurements in relevant studies.

III. Current Research Results

Next part lists several materials that have been used in flexible sensors.

A. Conductive Polymer Composites

Conductive polymer composites are generally an elastic composite material with a pressure-sensitive effect formed by uniformly dispersing the conductive particles in the insulating polymer composites. Although this kind of material has a certain pressure sensitivity, its sensitivity is not high. The pressure sensitivity strongly depends on the force deformation of the composite material, and the electrical signal has certain hysteresis.

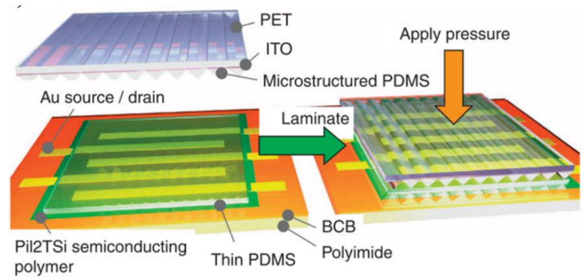


Fig. 2. Schematic representation of an OFET-type flexible pressure sensor made from a PDMS film with an inverted pyramid-type microstructure.

B. Sensitive Layer Surface Micro-structure

In the study of optimizing the flexible pressure sensor structure, the researchers found that by preparing periodic surface micro-structures, the contact resistance, generated between electrodes or micro-structures, is also a way to prepare excellent flexible piezoal resistance sensors. PDMS materials have become important materials for the preparation of micro-structure due to their excellent elasticity, chemical stability, biophase and plasticity. Fig. 2 shows the schematic representation of an OFET (Organic field-effect transistor)-type flexible pressure sensor made from a PDMS film with an inverted pyramid-type microstructure.

Due to high sensitivity, Sensors with micro-structure sensitive layer can measure small force. Flexible thin film pressure sensor is also applied on the field of organic field-effect transistor (OFET). This shouws the potential for the integration, low power consumption, etc.

C. Sponge Foam Structure and Carbon Skeleton

In addition to the method of preparing surface micro-structure on the sensitive layer, the method of making polymer material into sponge foam structure or carbon skeleton has become an important sensitive material of new flexible piezoresistive sensor with its advantages of light weight, high sensitivity, simple device making and low cost.

Weijie Liu has found new ideas from the melamine sponges we use in our daily scrubbing. After carbon nanotubes were adsorbed onto the sponge, the piezoresistive performance of the carbon skeleton material was greatly improved, and a flexible pressure sensor with higher sensitivity and more stability was prepared, as shown in Fig 3.

D. Electrical-Conductive Fabric and Paper

Inspired by flexible pressure sensors as wearable sensors, conductive fabric and conductive paper have also become a choice of new sensor-sensitive materials. Australia's Monash University use cotton paper soaked in gold nanowires solution methods to make gold nanowires coated on the cotton paper fiber technology, which made the cotton paper fiber has good

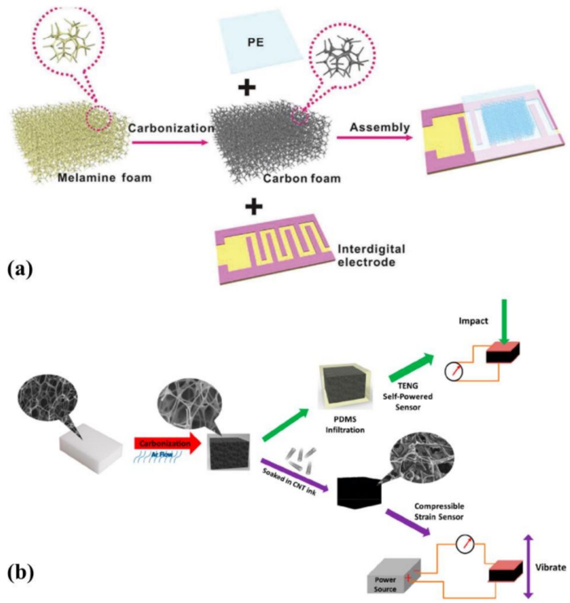


Fig. 3. (a) Schematic diagram of carbonization of melamine sponge and preparation of flexible pressure sensors; (b) Schematic diagram of carbonized melamine sponge packed in PDMS matrix to make friction generator and adsorbed CNT to make flexible pressure sensor

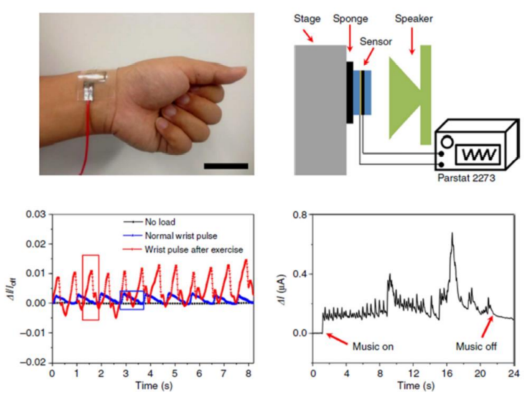


Fig. 4. Schematic diagram and signal response of gold nanowires/cotton paper fiber sensor in pulse measurement and non-contact sound measurement

electrical conductivity, and then puts sensitive material to the electrode to measure the pressure (fig. 4).

In the current study, a new sensor with force sensitivity mechanism, was developed by using the spider leg to simulate the bionic mechanism, which has a better performance in the field of feeling strain signals and vibration.

As mentioned above, the sensitive materials for flexible pressure sensors are developing towards the direction of structural diversification and diversified preparation methods, which is very important for the application of flexible pressure sensors in various different fields. Therefore, the following briefly introduces the research of flexible pressure sensor in new applications.

IV. Conductive Mechanism of Flexible Force Sensitive Film Materials

A. *Percolation Theory*

Polymer, epoxy resin, rubber and other polymer materials have excellent thermal insulation, electrical insulation corrosion resistance and mechanical properties, people add conductive filler as the second phase of these polymer materials to obtain the ideal electrical shielding, electric heating and antistatic materials. The volume fraction of the conductive phase in the composite which is just enough to form a conductive network after uniform dispersion is called percolation concentration or percolation point. When the volume fraction of the conductive phase is less than the percolation concentration, the composite is in an insulating state. When the volume fraction of the conductive phase is greater than the percolation concentration, the resistivity of the composite decreases sharply until the saturation of the conductive network. The variation trend of the resistivity is shown in the Fig.5.

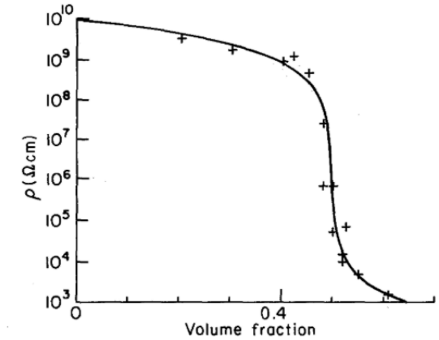


Fig. 5. The resistivity curve of conductive polymer composites vs. the content of conductive phase

Blaszkiewicz et al. used GEM(General Effective Media Theory) to explain the conductive phase. The GEM equation is as following equation:

$$\frac{(1-\phi)(\sigma_1^{1/t}-\sigma_m^{1/t})}{\sigma_1^{1/t}+(1-\phi_c)/\phi_c\sigma_m^{1/t}}+\frac{\phi(\sigma_h^{1/t}-\sigma_m^{1/t})}{\sigma_h^{1/t}+(1-\phi_c)/\phi_c\sigma_m^{1/t}}=0 \quad (4)$$

Assumed that the composite is an ideal insulator when no conductive network is formed in the composite and an ideal conductor when the conductive network is saturated, then $\sigma_1 = 0$ and $\sigma_h =$. The above formula can be simplified as:

$$1/\phi_m = (1/\phi_1)(1-\sigma/\sigma_c)^t \quad (5)$$

Where ϕ is the volume fraction of the conductive phase in the composite, ϕ_c is the percolation concentration. σ_1 is the conductivity of the composite before the formation of the conductive network, m is the conductivity of the composite when the conductive phase is ϕ, t is the index, and its value is related to the dimension of the formation of the conductive network in the composite.

When the concentration of the conductive phase is in the percolation zone, the conductive network begins to form to the saturation concentration zone of the conductive network At the same time, the deformation of the composite material caused by pressure will affect the distance between the conductive phases, and then change the complex A conductive network in the composite material, thus changing the resistivity of the composite material.

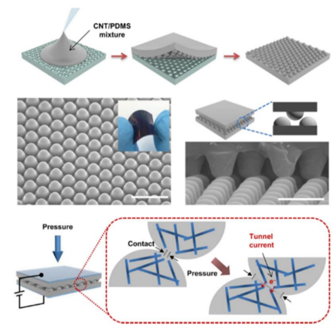
B. Channeling Effect

The current formed by electrons in a lower energy state with the probability of crossing a higher energy barrier is called a tunnel Electric current. In conductive polymer composite, the tunnel current effect means that the conductive phase in the composite is in When there is no contact with each other, a conductive channel with a certain resistance can be formed, which forms part of the conductive network.

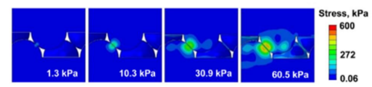
Based on percolation theory model and channeling effect model, a conductive polymer composite was constructed Conductive networks affected by deformation of polymer materials. However, under different pressures and stress variables, one model will dominate.

C. Surface Microstructure Effect

In addition to the resistance changes caused by the above two kinds of conductive network changes, the surface microstructure is also an important factor to improve the force sensitive performance of the flexible pressure sensor. Ulsan national institute of science and technology by comparing research of cyclical double hemisphere microstructure(Fig.6(a)), smooth and no single hemisphere microstructure microstructure sensor made of CNT/PDMS membrane, found and proves that the sensor can raise the sensitivity of the sensor sensitive layer surface microstructure, reduce the response time and improve the temperature stability. According to the finite element analysis, when the pressure is below 60.5kPa, the deformation of the sensitive membrane is basically concentrated on the microstructure, as shown in the Fig.6(b).



(a) Preparation method, surface morphology and sensitive mechanism



(b) Shape change of microstructure under different pressure

Fig. 6. Preparation of CNT/PDMS thin films with hemispherical surface microstructure and their surface morphology and sensitivity mechanism

V. Process and Material Selection

The flexible pressure sensor based on the conductive polymer composites has advantages of stable sensitivity and low cost. However, the sensitivity is based on the stress and deformation characteristics of polymer matrix in composite materials which leads to its sensitivity can not be high and it will smaller than 0.1 KPa^{-1}. Like sound vibrations and pulse, this kind of sensor will be no effect. Differently, the sensor based on the surface micro-structure can have high sensitivity and low reaction time but its disadvantage are low reaction range and high cost. So based on those two kinds, we want to select more reasonable material and preparation method to combine those advantages.

A. Selection of the preparation process

The preparation methods of conductive polymer composite film mainly include coating, screen printing and electrospinning. They have different peculiarity.

Coating method mainly is to use the spin coating method of conductive polymer composite material pulp evenly coated on the smooth surface to form a layer of thin film, then placed on the high temperature heat curing, to be thoroughly cured film, the film after stripping from the smooth plane shear into the shape of a need, make flexible thin film pressure sensor is sensitive to the layer.

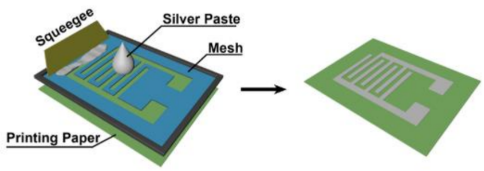
Screen printing process needs to design and prepare the corresponding screen in advance, and select the appropriate mesh number. Then prepare conductive polymer composite paste suitable for screen printing process, so that it can screen printing a complete, clear, flat screen printing film. Finally, the conductive polymer composite paste was printed on the corresponding substrate by automatic screen printing machine and then heated and solidified.

Electrospinning method mainly use the electrostatic spinning method will be collected through needles of conductive polymer composite silk in electrostatic substrate, a large number of composite yarn overlap connection to form a complete electrostatic spinning cloth is the process of non-woven fabric, and then to spin out the non-woven heated from the substrate after curing, made flexible pressure sensor is sensitive to the layer.

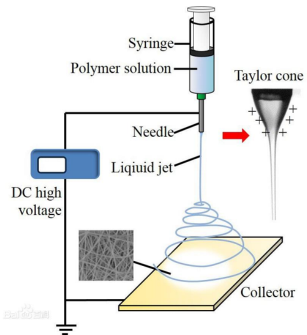
From the research and comparison of those three methods, we found that coating method don't need high-performance sizing agent while it will also produce low accuracy pattern. So we exclude the coating method. Then comparing the electrospinning and screen printing, we found although both of them need high-performance sizing agent, screen printing will be better in pattern accuracy and film thickness. Therefore, screen printing method is the best choose to fabricate sensitive layer and so on.

B. Selection of the conductive filler

Nowadays, carbon-based material has been the major selection of the conductive filler because of its good electrical



(a) Screen printing process



(b) Electrostatic spinning

conductivity and low cost. So we will choose our conductive filler from Carbon Black, Carbon Nanatube and Garphene.

Carbon nanotubes are easy to entangle and agglomeration, but not easy to disperse. Polymer materials with conductive properties are usually used in research.However, adding additional polymer material will change the physical properties of the final screen printing paste. So we don't use it.

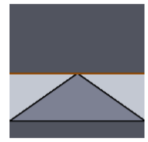
Graphene has excellent electrical conductivity, mechanical properties and so on. It's a good conductive filler. But graphene as a one-dimensional material, the conductive material is also prone to crimp and agglomeration in the polymer matrix material.

As a new type of carbon based material with high conductivity, easy dispersion and low cost, conductive carbon black helps to improve the stability of polymer materials and the service life of the material. Carbon black is a kind of amorphous carbon with a structure similar to amorphous graphite. Therefore, carbon black can meet the subject of flexible pressure sensor sensitive material requirements. So Carbon Black is the best conductive filler for our study.

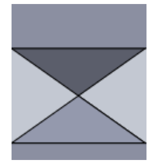
VI. Simulation

We have discussed which process and conductive filler is the most suitable, but in low pressure, microstructure is predominant in sensitivity. So in this part, we will design and simulate which microstructure has a better sensitivity.

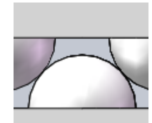
As the pressure sensitivity principle mentioned above, there are two main ways for pressure to cause current change. In essence, the change of electrical signal is realized through resistance change. Under low pressure, the change of contact surface between conductive layer structures is mainly caused by the deformation of microstructure, so as to realize the transformation of pressure to current signal. Under high pressure, the current change is mainly due to the extrusion



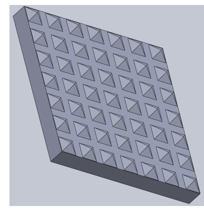
(a)



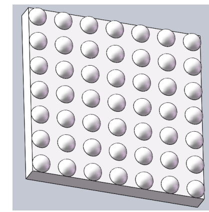
(b)



(c)



(d)



(e)

Fig. 7. Sectional drawing of (a) single pyramid, (b) dual pyramid, (c) dual hemisphere. The whole plane of (e) pyramid and (f) hemisphere.

connection of the conductive network of permeable material in the conductive layer, and the microstructure deformation has reached saturation at this time. In order to simplify the model, the simulation only considers the change of the contact surface between the structures caused by the deformation of the microstructure under small pressure, so as to reflect the change of resistance and current, and compares the difference of sensitivity under different microstructures. Due to the neglect of the current, there is only the mechanical structure simulation. In the simulation, both the substrate material and the microstructure material are selected PDMS, and further simplified as linear elastic material. The three mricostructure of simulation comparison are showed below Fig.7. They respectively are (a) single-pyramid structure, (b) dual-pyramid structure and (c) dual-hemisphere structure. The density of mono-layer microstructures is $7*7$, and the side length (or diameter) is $1\mu m*1\mu m$. $0-1kPa$ pressure was added to the upper surface of each structure to measure the change of contact surface with pressure, as shown in the Fig.8. Final simulation of pressure distribution are showed in Fig9 and we can find deformation occurs mainly on microstructure meaning conductive web has not be important yet.

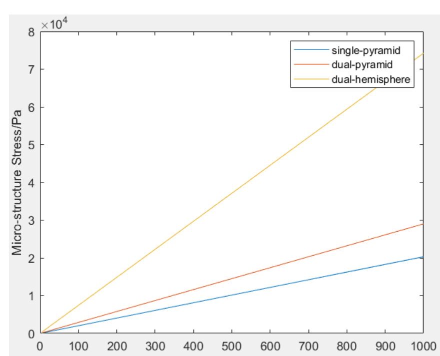
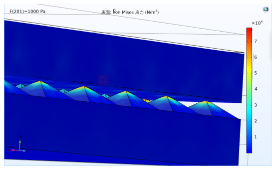
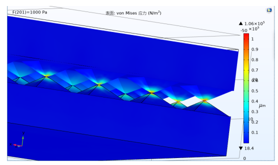


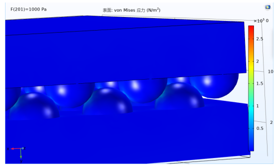
Fig. 8. Stress on mircostructure vs. surface loading



(a)



(b)



(c)

Fig. 9. Pressure distribution of (a) single pyramid, (b) dual pyramid, (c) dual hemisphere

By Equation(6) We can further calculate the curve of the contact surface with pressure, where S_l and S_m are loading and microstruction stress surface areas, P_l and P_m are loading stress of the two surface. But we can speculate: The contact surface does not change with pressure from Fig8 ahead because their slope are constant. What's worse, we get a eccentric conclusion: The surface of dual-hemisphere is smaller than dual-pyramid, which is smaller than single-pyramid.

$$\frac{S_l}{S_m} = \frac{P_m}{P_l} \tag{6}$$

$$S = \frac{\Delta I/I_0}{\Delta P} \propto (\frac{R_0}{R_t} - 1) \Rightarrow S \propto \frac{A_t}{A_0} - 1 = \frac{1}{SF} - 1 \tag{7}$$

$$SF = \frac{A_0}{A_t} = \frac{\textit{the contact area}}{\textit{total area could be contacted}} \tag{8}$$

Through other resources, we can infer the problem is caused because mesh division and setting might be wrong and the simulation calculates with the initial same surface all the time. However, it precisely present dual-hemisphere structure has the largest deformable contact surface and thus it has the best sensitivity. Since the simulation is rough, in order to further verify the sensitivity of different structure, we looked through other resources. Simulation is still under low pressure. As we all known, the deformation of the microstructure leads to the change of contact resistance, which leads to the increase of current. The sensitivity is defined as the change rate of current divided by the change amount of voltage, as Equation(7) shows, where $I_0(R_0)$ is original current or resistance without loading and $I_t(R_t)$ is current or resistance at a certain loadand surface factor SF. Hence, SF could quantify the capacity of contact area and further the resistance change of piezoresistive — the smaller SF is, the larger sensitivity is. In this paper, the surface factor of four typical microstructures – cylindrical, pyramid, hemispherical and ellipsoid microstructures are calculated, as Fig.10 showed.

The Fig.11 is obtained by COMSOL electro-mechanical simulation, which not only shows the microstrcutural deformation (a)(b)(c)(d), but also represent linear fitting curve (e)

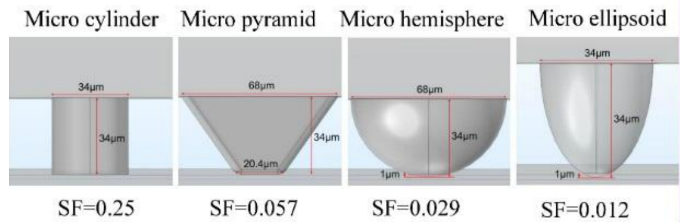


Fig. 10. mircostrcuture designed in the other paper

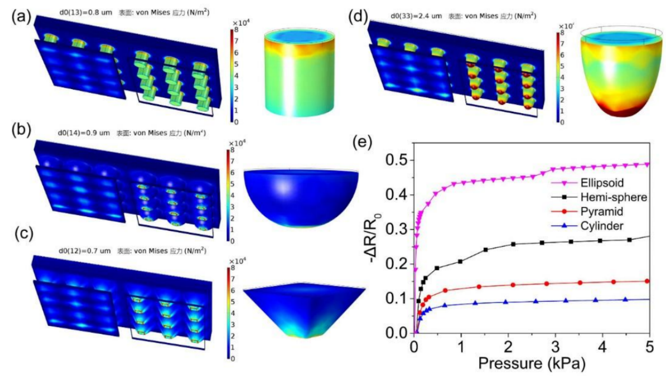


Fig. 11. Surface Von Mises stress of pressure sensors with (a) micro cylinders, (b)micro hemispheres, (c)micro pyramids and, (d) micro ellipsoids, respectively, (e) COMSOL simulation of -$\Delta R/R_0$ versus pressure plot.

of resistivity with pressure. From the TableI, the sensitivity can be seen more intuitively: semi ellipsoid$>$ semi sphere$>$ pyramid$>$ cylinder, which is basically consistent with our simulation results.

VII. The Future Application of Force-Sensitive Devices

Several kinds of nanostructure have been fabricated on the flexible substrate. In the last section, we successfully design the structure of device, and simulations have been proceeded by COMSOL. We can make sure that the device has the ability to detect the force applied on it. In this section, we will further explore the future application of our device. From the literature we refer to, there are about two main application fields.

A. Vibration Detect in the Environment

In our normal life there are several kinds of Vibrations. Some of them bring important information we need to know. For some machines, we can detect the work performance by detecting their vibration states. These vibrations have a particular of low amplitude and high frequency. Our device has

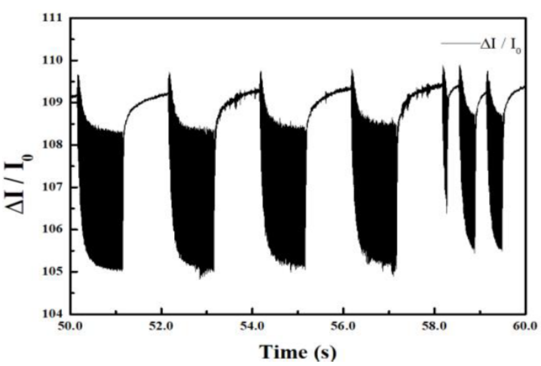
	Ellipsoid	Hemisphere	Pyramid	Cylinder
S_L/kPa^{-1}	12.23	1.90	0.96	0.64
SF	0.01	0.029	0.0057	0.025

TABLE I

Sensitivities of the pressure senors based on different mictostructures by linear fitting of COMSOL calculation results and the corresponding SF the potential to detect this kind of vibration. By watching the wave figure of the device, a detect system can be constructed in the factory and it will decrease the cost of operation.

Moreover, smart home system is now a famous develop path for technology. The smart home system requires the smart link between the furniture and web. Several kinds of sensors will play a tremendously important role in signal detection. Vibration is one of the normal signals appears in the real life. According to the work of Yu Jiangtao, a phone vibration detection is put out. He used the force-detect device to detect missing calls. From the signal wave, we can get the obvious

(a) The test condition



(b) The signal wave

Fig. 12. The force-detect device to detect missing calls

signal meaning the missing call. Using a wireless transmitter, the signal can be sent to the main computer.

B. Vibration Detect in the Wearable Equipment

Nowadays, the integration of electrics is a develop tendency for many companies. Flexibility is a primary requirement. By detecting the vibration of humans, we can get many information of human health. In literature, the detect of heartbeat is a typical application for force-sensitive device. Apart from breast, pulse is another way to detect the heartbeat. Some study have been proceeding as shown in the figure below: Every crest stands for one time of heartbeat. Moreover, observing every crest in detail, we can get the beat quality by P-wave, T-wave and D-wave. In this way, doctors can get the heartbeat state in an easy way.

Still some force-sensitive devices are used to detect the signal of voice. A study from BJFU shows that by clinging the

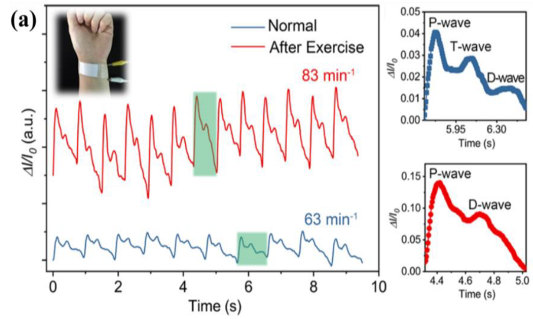


Fig. 13. The vibration detect for heartbeat

flexible device on the sore, the output signal can distinguish different words. They find different wave swings when people say different words. Moreover, a study from THU create an idea that make device product sounds. When the device is supplied an AC voltage, it can make the air around to expend due to the periodic joule heat. As a result, the device can product the sound wave at the frequency from $100Hz$ to $40kHz$. In this way, the device can act as a artificial throat.

C. Electronic Skin

Flexible electronic skin has been widely used in the mechanical field. The flexible force-sensitive device is adhered on the skin or robot arm to detect the force signal. To simulate the function of skin, the device need to detect several signals like static force, dynamic force, humidity and temperature. For the device we design in this project, it can detect the simple tough feel with the change of voltage wave. In some complicated design, the device can both detect the force and temperature by some particular materials and nanostructure. It may need a higher level of integrated circuit.

Acknowledgment

The preferred spelling of the word "acknowledgment" in America is without an "e" after the "g". Avoid the stilted expression "one of us (R. B. G.) thanks …". Instead, try "R. B. G. thanks…". Put sponsor acknowledgments in the unnumbered footnote on the first page.

References

[1] Y. Jiangtao. Fabrication of Flexible Pressure Sensitive Film Material and The Development of the Array Pressure Sensor. A Master Thesis Submitted to University of Electronic Science and Technology of China. 2019.

[2] J. C. Huang. Carbon Black Filled Conducting Polymers and Polymer Blends[J]. Advances in Polymer Technology, 2002, 21(4): 299–313.

[3] Y. Pang, H. Tian, L. Tao, et al. Flexible, Highly Sensitive, and Wearable Pressure and Strain Sensors with Graphene Porous Network Structure[J]. ACS Applied Materials and Interfaces, 2016, 8(40): 26458–26462.

[4] A. K. Appel, R. Thomann, R. Mülhaupt. Polyurethane Nanocomposites Prepared from Solvent-Free Stable Dispersions of Functionalized Graphene Nanosheets in Polyols[J]. Polymer, Elsevier Ltd, 2012, 53(22): 4931–4939.

[5] W. M. Huang, Y. Zhao, C. C. Wang, et al. Thermo/Chemo-Responsive Shape Memory Effect in Polymers: A Sketch of Working Mechanisms, Fundamentals and Optimization[J]. Journal of Polymer Research, VAN GODEWIJCKSTRAAT 30, 3311 GZ DORDRECHT, NETHERLANDS: SPRINGER, 2012, 19(9): 9952.

[6] E. Segal, R. Tchoudakov, M. Narkis, et al. Thermoplastic Polyurethane-Carbon Black Compounds: Structure, Electrical Conductivity and Sensing of Liquids[J]. Polymer Engineering and Science, 2002, 42(12): 2430–2439.

[7] S. M. Kim, H. Jeon, S. H. Shin, et al. Superior Toughness and Fast Self-Healing at Room Temperature Engineered by Transparent Elastomers[J]. Advanced Materials, 2018, 30(1): 1–8.

[8] M. Amjadi, Y. J. Yoon, I. Park. Ultra-Stretchable and Skin-Mountable Strain Sensors Using Carbon Nanotubes-Ecoflex Nanocomposites.[J]. Nanotechnology, IOP Publishing, 2015, 26(37): 375501.