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Piezoresistive Flexible Strain Sensors: An Overview of Progress, Applicability and Limitations

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Strain sensors exhibit tremendous potential applications in health monitoring, bio-sensing, electronic skin, and tactile perception and hence researchers have developed keen interest in the development of high-performance flexible and stretchable sensors. In this paper, recent developments in the piezoresistive polymer composite-based flexible strain sensor is reviewed. The primary requirement of wearable sensor technology is of course sensitivity and flexibility which is difficult to achieve with conventional sensors. Various parameters governing strain sensors viz. sensitivity, gauge factor, linear relationship between input and output, detection limit, response speed and reliability are discussed here. Representative types of strain sensors and relevant working principles are then described. The applications of strain sensors in human computer interaction, human health monitoring, marine and structure health monitoring are also discussed. Finally, future scope for the development of more versatile flexible wearable strain sensors is elaborated.

Keywords: Electrodes, Health monitoring, Piezoresistivity, Response speed, Reliability, Wearable devices

1. Introduction

Flexible wearable technology has gained a lot of popularity over recent years. There is huge demand for wearable devices that can ensure real time monitoring of data and control activities through it. Smart watches and bands are burning examples of wearable technology. People track their movement and pulse rate etc. using these watches. The problem with these devices is their stiffness and rigidity. Consequently, such devices find it hard to conform to the uneven topology of human skin. Being an electronic device for detecting and transmitting data, the strain sensor has the ability to perceive strain signals and transform them into corresponding electrical signals. This enables the sensor to collect, transmit, process, analyze, and display information. Human body motion detection [1], health monitoring [2], wearable electronic gadgets [3,4] etc. have recently gained popularity in the field of strain sensors. The conventional strain sensor based on Micro-Electro-Mechanical Systems (MEMS) mainly consists of metal, semiconductors, piezoelectric crystals, etc., which are usually rigid materials. The technique of utilizing these materials to fabricate strain sensors is proven and can precisely achieve remarkable performance in terms of low measurement errors and mass fabrication [5,6]. However, their drawbacks include the large volume and limited deformation. Therefore, developing flexible strain sensors which are capable of bending and deforming without losing performance over repeated cycles is vital for expanding their potential uses in wearable devices and robotic arms.

Based on different mechanisms of various conductive materials, flexible strain sensors are mainly divided into five categories, viz. piezoresistive. iontronic, piezoelectric, triboelectric and capacitive as shown in Fig.1.

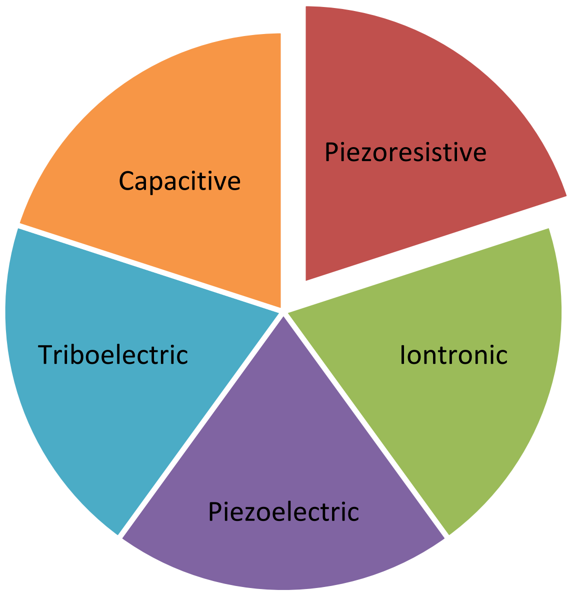


Fig. 1 Various types of Flexible Strain Sensors

Among these, piezoresistive sensors which exhibit high sensitivity and enhanced durability are the most widely used flexible sensors. Piezoresistive strain sensors generally comprise of two-phases viz. the conductive phase and the substrate phase [7] and these are designed in shapes that are flexible such as membranes. The conductive phase controls the sensing properties of the sensors, and the substrate phase ensures the shape and structural integrity of the piezoresistive sensors. Concentration of the conductive and substrate materials is changed to improve the functional properties of the piezoresistive strain sensor [8]. Whenever required an extra filler is added to the composite to make a tunable sensor. In spite of all these innovations, existing composites still face limitations viz. low sensitivity for minor strain, decreased sensing capability due to material fatigue on prolonged use and plastic deformation of the substrate material after a specified number of repeated cycles.

2. Parameters for Strain Sensors

The various parameters which decide the performance of piezoresistive materials [9] are shown in Fig. 2.

2.1 Sensitivity and gauge factor

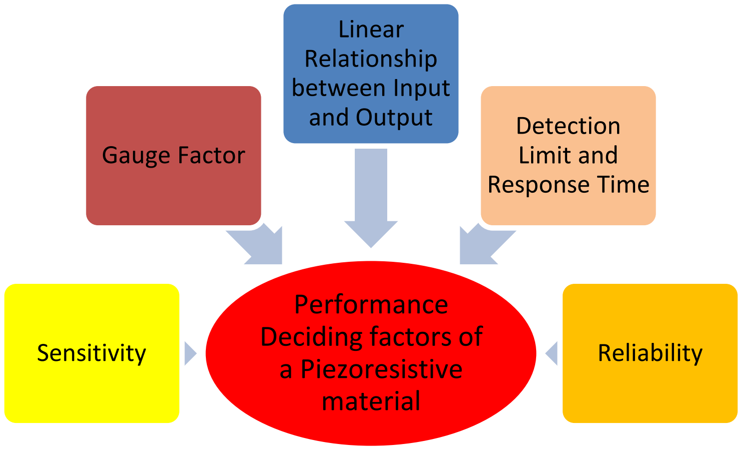


Fig.2. Parameters responsible for the performance of piezoresistive materials

The sensitivity and gauge factor (G) are the two major parameters which are used for analyzing piezoresistive behavior of the membranes. The sensitivity of the composite is calculated using Eq. [1]

$$\text{Sensitivity} = \Delta R / R_0 \quad [1]$$

Where ΔR represents the change in resistance obtained on bending the membrane and R_0 the initial resistance without bending. The Gauge factor (GF)is defined as the ratio of the sensitivity to strain (ε) and is calculated using Eq. [2].

$$GF = \Delta R / (\varepsilon \times R_0) \quad [2]$$

2.2 Linear relationship between input and output

The linear response range refers to the range in which the output signal is proportional to the input. Theoretically, flexible strain sensors should have ideal linear relationship between input and output over entire range of sensing, but practically the linear range is often only a part of the full range.

2.3 Detection limit and response speed

The detection limit refers to the minimum physical quantity that the sensor can measure with a certain precision or repeatability. The response speed is a measurement of how quickly a sensor reacts to the changes in stimuli. For a sensor to be efficient detection limit should be small and it should possess a high response speed.

2.4 Reliability

The reliability of a strain sensor refers to the ability of its components and equipment to maintain the same function and performance under repeated cycles over a prolonged period of time. The higher the reliability of the sensor, the more stable and accurate it can measure strain,

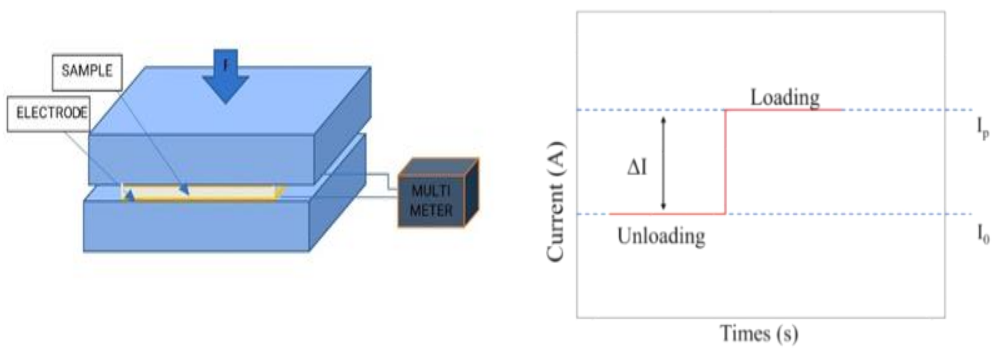
3. Piezoresistivity Measurement

The phenomenon of converting changes in strain into a corresponding change in resistance is the guiding principle of piezoresistive pressure sensors. The resistance of the material is regulated by Eq. [3]

$$R = \rho l/a \qquad [3]$$

In this equation, ρ is the material's specific resistance, l is the length, a is the cross-sectional area, and R is the resistance.

In the absence of any strain, the polymer composite material exhibits high resistance, and the sensor can only allow weak current, Io to pass through it. External mechanical stresses cause compression or tension on the piezoresistive strain sensor, which results in an increase in the output current. Therefore, the piezoresistive strain sensor, via the variation in resistance or output current, reflects the variation of strain as shown in Fig. 3.



(a) (b)

Fig. 3 Working Principle of piezoresistive strain sensors; (a) Application of stress (b) Corresponding current under loading and unloading conditions

4. Materials Involved in Fabrication: Merits and Limitations

The materials involved in the fabrication of flexible piezoresistive strain sensors as exhibited in Fig. 4 are:

4.1 Conductive materials

The conductive layer comprises of the conductive polymer composite formed by mixing conductive fillers and insulative elastomer or conductive nanomaterials coated on insulative elastomer substrates. Materials of the conductive part are divided into three categories viz. metallic materials, carbon-type nanomaterials and hybrid materials.

4.1.1 Metallic fillers

Metallic fillers such as Cu, Ag and Au are generally used. Such fillers in the form of nanoparticles [10,11] and nanowires [12,13], exhibit good electrical properties and flexibility. As the inter particle gap between metallic nanoparticles is generally very less, conduction takes place via quantum tunneling effect. As this effect is highly sensitive to the distance change amongst particles, even a minor change in strain will result in destruction and regeneration of the conductive network, causing a huge change in resistance. Such sensors thus exhibit high sensitivity and gauge factor. CuNWs, however easily gets oxidized and require further modification to mitigate this issue [14].

4.1.2 Carbon family fillers

Carbon family nanomaterials i.e Carbon Black (CB), Carbon Nano Tubes (CNTs) and graphene, possess excellent electrical properties. [15,16]. In recent years, various polymer composites have been developed for piezoresistive strain sensors, including carbon nanotube (CNT) [17,18], carbon black (CB) [19,20], and carbonyl iron powder (CIP) [21]. Zhao et al. developed a sensor based on hierarchically structured CNT/PDMS film (h-CNT/PDMS) by blade coating techniques using sandpaper as the substrate [22]. However, the problem with CB is that it tends to agglomerate easily and therefore it is difficult to disperse in the matrix because of its tiny particle size. Also, a high dose is required to obtain good conductivity, which leads to compromised stretchability. In addition, the conductive paths amongst CB particles are easily disrupted and reformed under strain, causing unstable sensing capabilities. However, compared to CNTs and graphene, CB is relatively cheaper, which makes a good candidate for fabricating low cost strain sensors. Graphene is a hexagonal carbon nanomaterial with a honeycomb lattice structure comprising of hybrid orbital carbon atoms. It's high transmittance (90%), large surface area per unit mass (2630 m^2/g) and excellent thermal and mechanical properties, high ductility, high recovery, high elastic stiffness (340 N/m) and good carrier mobility at room temperature, makes it a desirable conductive filler for flexible strain sensors with good sensing performance and stability [23].

4.1.3 Hybrids

Hybrid materials e.g. soft AuNWs and hard AgNWs were collectively used to fabricate stretchable transparent films [24]. These exhibited a broad strain range of 0.05–70% and an enhanced sensitivity of 236.6 within the 5% strain level. In the same way a hybrid film consisting of CB and CNTs displayed high sensitivity, durability and consistent electrical behavior under many sensing cycles owing to the synergistic effect of conductive network formed by CNTs and CB jointly [25]. Besides these, combinations of MWCNTs and CB [26], CNTs and graphene [27,28], have been reportedly shown improved performance. Conclusively it can be said that hybrid fillers exhibit various benefits like improved electrical conductivity, sensing properties and stretchable range in flexible piezoresistive sensors.

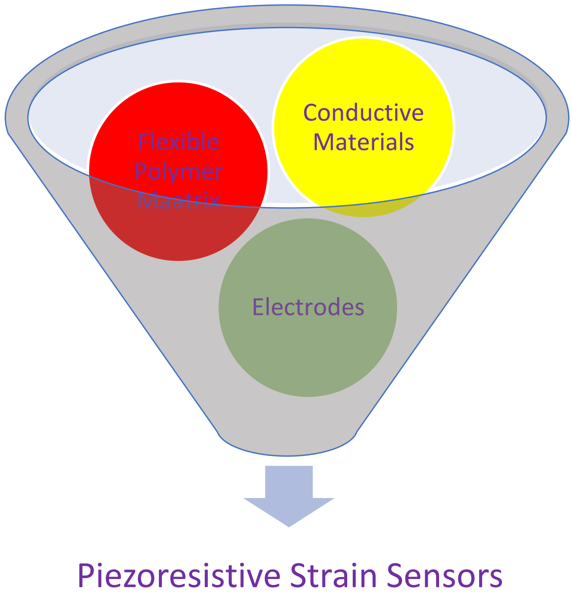


Fig. 4 Materials involved in the fabrication of flexible piezoresistive strain sensors

4.2 Flexible polymer matrix

Flexible polymer matrix provides a large stretchable range for piezoresistive sensors. Most commonly used flexible substrates for a wide range of applications are polydimethylsiloxane (PDMS) [29], Ecoflex [30] and thermoplastic polyurethane (TPU) [31]. PDMS is the most widely used substrate for fabricating flexible sensors. due to its lower elastic modulus value, excellent elasticity, good formability, high transparency, good thermal stability and corrosion resistance. However, PDMS is sensitive to temperature change and ageing affects its performance in the long run. Ecoflex has excellent mechanical flexibility, water resistance and long-term stability. Amjadi et al. [30] employed Ecoflex, the first biodegradable polymer, as matrix and CNTs as conductive filler to fabricate an ultra soft strain sensor. Strong interface between the CNTs and the Ecoflex resulted in a flexible sensor which possess high reliability and linearity and a broad strain range [29]. Thermoplastic polyurethane (TPU) possess higher toughness and tear strength besides stronger resistance to mechanical damage as compared to PDMS. Thus, TPU based sensors which exhibit good repeatability over more than 1000 loading cycles, has gradually become a common matrix material for flexible sensors recently [30,31]. Other polymers viz. polyimide (PI) [32], polyurethane [33], polyvinyl alcohol [34] and polyethylene terephthalate [35,36], have also been employed as matrix in different fillers.

It is found that the properties of different piezoresistive sensors are quite different from each other, even though they have the same conductive filler. Another peculiar aspect that is noticed is that a flexible sensor can't simultaneously exhibit high GF, wide detectable range and good linearity. A sensor with a relatively large range and high GF has been found exhibiting a nonlinear strain-resistance relation, whereas a sensor possessing large range and excellent linearity fails to give a high GF. Hence, the sensing properties needs be improved to fabricate more versatile sensors.

4.3 Electrodes

Electrodes are indispensable in strain sensors as these serve as connections between a sensor and a signal measuring electronic device. As electrical signals from the sensor are communicated to the measuring device through electrodes, these should possess excellent conductivity and stability during the service period of the strain sensor. Metallic electrodes involving aluminum, copper, silver and gold are the most commonly used for most sensing applications. Stretchable electrodes based on metallic nanoparticles or nanowires, ionic hydrogels and conductive polymers have been widely studied [37-40]. Further research is required to reduce contact resistance and to develop low cost electrode materials.

5. Applications

Piezoresistive flexible strain sensors find wide applications in various sectors as depicted in Fig. 5.

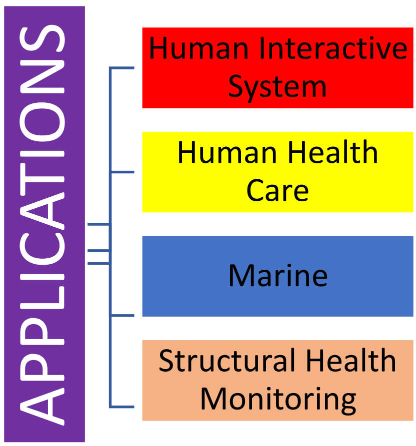


Fig. 5. Major applications of piezoresistive flexible strain sensors

5.1. Human-interactive system

Human–computer interaction (HCI) is pivotal to ensure proper interaction between humans and the digital world, and the data acquisition here is mainly dependent on input stimuli [41]. Electronic skin and multi pixel touchpads based on flexible sensor arrays are becoming a frontline trend in this field [42,43]. These possess various advantages like high sensitivity, compact size, excellent stability, and a relatively simple and cost effective manufacturing process. To build a tactile keyboard, Pyo et al. prepared a tactile sensor consisting of stacked CNTs and Ni-fabrics [44]. Flexible electronics based on multifunctional fabrics are gaining attention because of light weight and ease of fabrication besides being flexible [45]. Layered structure of the fabric enhances the area of contact and distributes the stress all over the fabric, increasing both sensitivity and linearity. The device exhibits a sensitivity of 26.13 kPa^{-1} over a pressure range of 0.2~982 kPa. The sensors were used to make a keyboard consisting of 29 tactile sensor cells corresponding to all 26 letter keys, a comma, a dot, and a space bar. The sensor array consisted of fourteen electrical lines fabricated by the row-column selection wiring procedure. Using a tactile sensor with 64 × 64 pixels, Zhao et al. collected 3099 images of handwritten digits, realizing a classification accuracy of 98.8% for testing.

Smart tactile gloves are becoming one of the most important branches of HCI. As human hands perform lots of the tasks in daily work, projecting hand movements and using them to control robots or virtual objects has become instrumental in doing work, playing as well as learning. Currently, the relatively mature technology in smart gloves use inertial measurement units (IMU) to measure hand movement. Such gloves exhibit good accuracy and repeatability in tracking angular motion of fingers owing to the advanced MEMS technology [46]. However, exclusively IMU-based gloves are unable to monitor stress, particularly when seeking information about touch. Therefore, piezoresistive material-based sensors have gained importance as supplement for smart glove sensing. Besides this, combining tactile perception with remote feedback can be used to build remote sensing devices. The system generally incorporates a sensor at the remote end, supports by a communication device for haptic data feedback, and an actuator as stimuli at the user end. Recently researchers developed a tactile interface comprising of the tactile glove, a linear-actuator-based tactile display, and two microcontroller units (MCUs) for data handling and wireless communication. The tactile information sensed by user A was measured by the wearable tactile glove, while simultaneously, the actuator-based tactile display provided tactile information to user B. The construction can also be built into a teleoperation system [47,48], which is the user-side control of a robot in a remote scene to perform tasks, such as the manipulation of objects, which has great potential for various applications, e.g., tele-robotic surgery and virtual reality. The tactile feedback is crucial for the planning of the movement and controlling applied force.

5.2 Human health care

Strain sensors can be utilized in hospitals; as large data acquisition is required there. With the use of these sensors it becomes easy to collect such huge data. The new technology is thus ensuring application of machine learning algorithms to help automatic diagnosis. Plantar and pulse measurements are two main applications of the strain sensors in the medical field. Additionally, artificial skin fabricated using flexible strain sensors is also often used in prosthetics to reconstruct the skin's sensing response to the vital characteristics of external stimuli. The measurement of plantar load distribution has a number of applications, including disease diagnosis, rehabilitation, athletic analysis, etc. Wrist pulse signals can detect multiple health information, e.g., heart rate, blood pressure, vascular function, etc. Wearable strain sensors for wrist pulse rate information are thus the most widely studied sensors now-a-days. Since the pulse is weak and the corresponding impulse signal generated is feeble too, new materials are continuously being developed for pulse monitoring having high sensitivity and fast response. Noting that higher sensitivity may amplify both the target signal and the noise, it is also necessary to take signal-noise ratio (SNR) into consideration while optimizing the sensor sensitivity. Recently a wearable prototype device was fabricated by Y Zhuang [49] for facial expression, pulse signal, blowing and joint bending motion monitoring.

5.3. Marine

The measurement of strain changes also has applications in marine engineering. In the underwater world, by attaching strain sensors to marine animals, their behaviors and marine environment can be explored [50]. Bulky and rigid sensors may influence animal behavior; thus, flexible, conformable and lightweight piezoresistive sensors are preferred. Moreover, the arrayed sensor can provide more detailed water conditions. Flexible strain sensors are promising to be the futuristic devices for marine bio-logging. Besides biology and ecology, flow monitoring of marine vehicles can also be carried out. In the sea, the interaction between the body of the ship and the water will affect the travel and overall maneuvering which can be monitored by strain sensors.

5.4 Structural health monitoring (SHM)

Earlier cement-based embedded piezoresistive sensors were being applied in concrete structures as these possess excellent sensitivity and reasonably good linearity. However, it has been found that sensing performances of these cement-based strain sensor are affected by ambient temperature and humidity. Poor plasticity also limited their use in large deformation monitoring [51,52]. Contrary to it, conductive polymer-based flexible piezoresistive strain sensors are capable of overcoming the above limitations as these possess high sensitivity besides being compatible with large stretchability. These properties are helpful in monitoring not only strain but also cracks or damages in bridges, giant structures and high-rise buildings [53]. Flexible piezoresistive sensors are thus being increasingly used in SHM of concrete structures.

6. Conclusion

In this review, a gist of the recent developments in flexible piezoresistive strain sensors based on polymer composite materials is given. The feasibility of wearable piezoresistive devices for different purposes like health monitoring, electronic skin, and human motion detection are discussed. The applications of piezoresistive flexible in marine and structure safety monitoring is also discussed. In future, polymer-based piezoresistive sensors are expected to have more advantages over other sensors or sensing technologies due to high sensitivity, low cost, simple fabrication, and biocompatibility. Some of the potential applications of these sensors include artificial organs, electronic skin and health monitoring. To make these sensors versatile, research need to be done in the area of: (1) Developing novel polymer materials or composites with tunable electrical and mechanical properties. (2) Improving the sensitivity to detect even small changes in strain. (3) to develop multifunctional sensors to detect parameters like temperature and humidity too (5) Optimizing the fabrication methods to produce cost effective strain sensors for practical applications. (6) ensuring reliability and durability under various continuously fluctuating environmental conditions.

Disclosure Statement

No potential conflict of interest was reported by the authors.

References

1. B. Chen, L. Zhang, H. Li, X. Lai and X. Zeng, "Skin-Inspired Flexible and High-Performance M Xene polydimethylsiloxane Piezoresistive Pressure Sensor for Human Motion Detection," J.

Colloid Interface Science, 617, 478–488, 2022.
2. Y. S. Oh, J.-H. Kim, Z. Xie, S. Cho, H. Han, S. W. Jeon, M. Park, M. Namkoong, R. Avila and Z. Song, "Battery-Free, Wireless Soft Sensors for Continuous Multi-Site Measurements of Pressure and Temperature from Patients at Risk for Pressure Injuries," Nat. Commun., 500, 12, 2021.
3. S. Sharma, A. Chhetry, M. Sharifuzzaman, H. Yoon and J. Y. Park, "Wearable Capacitive Pressure Sensor Based on MXene Composite Nanofibrous Scaffolds for Reliable Human Physiological Signal Acquisition," ACS Appl. Mater. Interfaces, 12, 22212–22224, 2020.
4. J. Yu, X. Hou, M. Cui, S. Zhang, J. He, W. Geng, J. Mu and X. Chou, "Highly Skin-Conformal Wearable Tactile Sensor Based on Piezoelectric-Enhanced Triboelectric Nanogenerator," Nano Energy, 64, 103923, ,2019.
5. X. Huang, J. He, L. Zhang, F. Yang and D. Zhang, "A Novel Pressure Sensor Design for Low Pressure Ranges," in Proc. of the 2014 IEEE International Conference on Electron Devices and Solid-State Circuits, Chengdu, China, June 2014, 18-20.
6. T. Xu, H. Wang, Y. Xia, Z. Zhao, M. Huang, J. Wang, L. Zhao, Y. Zhao and Z. Jiang, "Piezoresistive Pressure Sensor with High Sensitivity for Medical Application Using Peninsula-Island Structure," Front. Mech. Eng., 12, 546–553, 2017.
7. J. Z. Su, Y. Xia, L. D. Zhu, H. P. Zhu and Y. Q. Ni, "Typhoon- and temperature-induced quasi-static responses of a supertall structure," Eng. Struct., 143, 91–100, 2017.
8. D. Y. Choi, M. H. Kim, Y. S. Oh, S. H. Jung, J. H. Jung, H. J. Sung, H. W. Lee and H. M. Lee, "Highly Stretchable, Hysteresis-Free Ionic Liquid-Based Strain Sensor for Precise Human Motion Monitoring," ACS Appl. Mater. Interfaces, 9, 1770, 2017.
9. Wen-Tao Guo, Xin-Gui Tang, Zhenhua Tang and Qi-Jun Sun, "Recent Advances in Polymer Composites for Flexible Pressure Sensors," Polymers, 15(9), 2176, 2023.
10. D. Jang, S. Z. Farooq, H. N. Yoon and H. R. Khalid. "Design of a Highly Flexible and Sensitive Multi-Functional Polymeric Sensor Incorporating CNTs and Carbonyl Iron Powder," Compos. Sci. Technol., 207, 108725, 2021.
11.Y. Zhao, T. Shen, M. Zhang, R. Yin, Y. Zheng, H. Liu, H. Sun, C. Liu and C. Shen, "Advancing the Pressure Sensing Performance of Conductive CNT/PDMS Composite Film by Constructing a Hierarchical-Structured Surface," Nano Mater. Sci., 5, 343-350, Dec 2023.
12. A. Reizabal, S. Gonçalves, N. Pereira, C. M. Costa, L. Pérez, J. L. V. Vilela and S. L. Mendez "Optically Transparent Silk Fibroin/Silver Nanowire Composites for Piezoresistive Sensing and Object Recognitions," Journal of Materials Chemistry C, 37, 13053-13062, Aug 2020
13. Y. X. Li, D. Y. Han, C. J. Jiang, E. Q. Xie and W. H. Han,"A Facile Realization Scheme for Tactile Sensing with a Structured Silver Nanowire-PDMS Composite," Adv. Mater. Technol., 4, 1800504, 2019.
14. Y. Zhu, Y. G. Hu, P. L. Zhu, T. Zhao, X. W. Liang, R. Sun and C. P. Wong, "Enhanced oxidation resistance and electrical conductivity copper nanowires-graphene hybrid films for flexible strain sensors," New J. Chem., 41, 4950–4958, 2017.
15. J. J. Wu, H. Q. Li, X. J. Lai, Z. H. Chen and X. R. Zeng, "Conductive and superhydrophobic F-rGO@CNTs/chitosan aerogel for piezoresistive pressure sensor," Chem. Eng. J., 386, 123998, 2020.
16. Q. Zheng, J-H Lee, X. Shen, X. Chen and J-K Kim "Graphene-based wearable piezoresistive physical sensors," Materials today, 36, 158-179, Jan 2020
17. Q. Ma, B. Hao, X. Yue and P.-C. Ma "Matrix Dominated Positive/Negative Piezoresistance in Conducting Polymer Nanocomposites Reinforced by CNT Foam," Polymer, 257, 12528, 2022.
18. Y. Wang, H. Mao, Y. Wang, P. Zhu, C. Liu and Y. Deng "3D Geometrically Structured PANI/CNT-Decorated Polydimethylsiloxane Active Pressure and Temperature Dual-Parameter Sensors for Man–Machine Interaction Applications," J. Mater. Chem. A, 8, 15167–15176, 2020.
19. J. Yuan, Q. Li, L. Ding, C. Shi, Q. Wang, Y. Niu and C. Xu "Carbon Black/Multi-Walled Carbon Nanotube-Based, Highly Sensitive, Flexible Pressure Sensor," ACS Omega, 7, 44428–44437,

2022.

20. K. Liu, J. Yu, Y. Li, X. Yan, D. Bai, X. Liao, Z. Zhou, Y. Gao, X. Yang and L. Li "Carbon Black from Diesel Soot for High-Performance Wearable Pressure Sensors," Adv. Mater. Technol., 4, 1900475, 2019.
21. D. Jang, S. Z. Farooq, H. N. Yoon and H. R. Khalid "Design of a Highly Flexible and Sensitive Multi-Functional Polymeric Sensor Incorporating CNTs and Carbonyl Iron Powder," Compos. Sci. Technol., 207, 108725, 2021.
22. Y. Zhao, T. Shen, M. Zhang, R. Yin, Y. Zheng, H. Liu, H. Sun, C. Liu and C. Shen, "Advancing the Pressure Sensing Performance of Conductive CNT/PDMS Composite Film by Constructing a Hierarchical-Structured Surface," Nano Mater. Sci., 5, 343-350, Dec 2023.
23. D. P. Hao, R. X. Yang, N. Yi, H and Y. Cheng "Highly sensitive piezoresistive pressure sensors based on laser-induced graphene with molybdenum disulfide nanoparticles," Sci. China Technol. Sci., 64, 2408–2414, 2021.
24. M.D. Ho, Y. Ling, L.W. Yap, Y. Wang, D. Dong, Y. Zhao, W. Cheng. "Percolating Network of Ultrathin Gold Nanowires and Silver Nanowires towards Invisible Wearable Sensors for Detecting Emotional Expression and Apexcardiogram". Adv. Funct. Mater., 27, 1700845, 2017
25. L. Lin, S. Y. Liu, Q. Zhang, X. Y. Li, M. Z. Ji, H. Deng and Q. Fu "Towards Tunable Sensitivity of Electrical Property to Strain for Conductive Polymer Composites Based on Thermoplastic Elastomer," ACS Appl. Mater. Interface, 5, 5815–5824, 2013.
26. N. Y. Ning, S. S. Wang, L. Q. Zhang, Y. L. Lu, M. Tian and T. W. Chan, "Synchronously Tailoring Strain Sensitivity and Electrical Stability of Silicone Elastomer Composites by the Synergistic Effect of a Dual Conductive Network," Polymers, 8, 100, 2016.
27. K. Ke, P. Potschke, N. Wiegand, B. Krause and B. Voit "Tuning the Network Structure in Poly (vinylidene fluoride)/Carbon Nanotube Nanocomposites Using Carbon Black: Toward Improvements of Conductivity and Piezoresistive Sensitivity," ACS Appl. Mater. Interfaces, 8, 14190–14199, 2016.
28. H. Liu, J. C. Gao, W. J. Huang, K. Dai, G. Q. Zheng, C. T. Liu, C. Y. Shen, X. R. Yan, J. Guo and Z. H. Guo, "Electrically conductive strain sensing polyurethane nanocomposites with synergistic carbon nanotubes and graphene bifillers," Nanoscale, 8,12977–12989, 2016.
29. Y. J. Gao, H. Ota, E. W. Schaler, K. Chen, A. Zhao, W. Gao, H. M. Fahad, Y. G. Leng, A. Z. Zheng, F. R. Xiong, et al., "Wearable Microfluidic Diaphragm Pressure Sensor for Health and Tactile Touch Monitoring," Adv. Mater., 29, 1701985, 2017.
30. M. Amjadi, Y. J. Yoon and I. Park, "Ultra-stretchable and skin-mountable strain sensors using carbon nanotubes-Ecoflex nanocomposites," Nanotechnology, 26, 375501, 2015.
31. Y. J. Chen, Y. Li, D. H. Xu and W. T. Zhai "Fabrication of stretchable, flexible conductive thermoplastic polyurethane/graphene composites via foaming," RSC Adv., 5, 82034–82041, 2015.
32. X. P. Gan, J. Z. Wang, Z. H. Wang, Z. Zheng, M. Lavorgna, A. Ronca, G. X. Fei and H. S. Xia "Simultaneous realization of conductive segregation network microstructure and minimal surface porous macrostructure by SLS 3D printing," Mater. Des., 178, 107874, 2019.
33. Y. Zhao, J.-G. Song, G. H. Ryu, K. Y. Ko, W. J. Woo, Y. Kim, D. Kim, J. H. Lim, S. Lee and Z. Lee, "Low-temperature synthesis of 2D MoS2 on a plastic substrate for a flexible gas sensor," Nanoscale, 10, 9338–9345, 2018.
34. T. Vuorinen, J. Niittynen, T. Kankkunen, T. M. Kraft and M. Mantysalo "Inkjet-Printed Graphene/PEDOT: PSS Temperature Sensors on a Skin-Conformable Polyurethane Substrate," Sci. Rep., 6, 35289, 2016.
35. G. Hassan, M. U. Khan, J. Bae and A. Shuja, "Inkjet printed self-healable strain sensor based on graphene and magnetic iron oxide nano-composite on engineered polyurethane substrate," Sci. Rep., 10, 18234, 2020.
36. Y. Z. N. Htwe, W. S. Chow, G. Suriati, A. A. Thant and M. Mariatti "Properties enhancement of

graphene and chemical reduction silver nanoparticles conductive inks printed on polyvinyl alcohol (PVA) substrate," Synth. Met., 256, 116120, 2019.
37. M. Y. Zheng, W. Y. Li, M. J. Xu, N. Xu, P. Chen, M. Han and B. Xie "Strain sensors based on chromium nanoparticle arrays," Nanoscale, 6, 3930–3933, 2014.
38. T. Liu, M. M. Liu, S. Dou, J. M. Sun, Z. F. Cong, C. Y. Jiang, C. H. Du, X. Pu, W. G. Hu and Z. L. Wang, "Triboelectric-Nanogenerator-Based Soft Energy-Harvesting Skin Enabled by Toughly Bonded Elastomer/Hydrogel Hybrids," ACS Nano, 12, 2818–2826, 2018.
39. H.G. Wu, Q. Liu, W.C. Du, C. Li and G. Q. Shi, "Transparent Polymeric Strain Sensors for Monitoring Vital Signs and Beyond," ACS Appl. Mater. Interfaces, 10, 3895–3901, 2018.
40. W. H. Yeo, Y. S. Kim, J. Lee, A. Ameen, L. Shi, M. Li, S. Wang, R. Ma, S. H. Jin, Z.Kang, Y Huang and J.A. Roggers ,"Multifunctional Epidermal Electronics Printed Directly onto the Skin," Advanced. Materials, 25, 2773–2778, Feb 2013.
41. Shuoyan Xu, Zigan Xu, Ding Li et.al. "Recent Advances in Flexible Piezoresistive Arrays: Materials, Design, and Applications," Polymers, 15(12), 2699, 2023.
42. M. Zhu, T. He and C. Lee "Technologies toward next Generation Human Machine Interfaces: From Machine Learning Enhanced Tactile Sensing to Neuromorphic Sensory Systems," Appl. Phys. Rev., 7, 031305, 2020.
43. Y. Guo, Z. Guo, M. Zhong, P. Wan, W. Zhang and L. Zhang "A Flexible Wearable Pressure Sensor with Bioinspired Microcrack and Interlocking for Full-Range Human-Machine Interfacing," Small, 14, 1803018, 2018.
44. S. Pyo, J. Lee, W. Kim, E. Jo and J. Kim,"Multi-Layered, Hierarchical Fabric-Based Tactile Sensors with High Sensitivity and Linearity in Ultrawide Pressure Range," Adv. Funct. Mater., 29, 1902484, 2019.
45. J. S. Heo, J. Eom, Y.-H. Kim and S.K. Park "Recent Progress of Textile-Based Wearable Electronics: A Comprehensive Review of Materials, Devices, and Applications," Small, 14, 1703034, 2018.
46. B. O'Flynn, J. Torres, P. Angove, J. Connolly, J. Condell, K. Curran, , "Novel Smart Sensor Glove for Arthritis Rehabilitation," in Proc. of the 2013 IEEE International Conference on Body Sensor Networks, Cambridge, MA, USA, 6–9 May 2013, 1–6.
47. C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward and D. Prattichizzo "Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives," IEEE Trans. Haptics, 10, 580–600, 2018.
48. C. Bartolozzi, L. Natale, F. Nori and G. Metta "Robots with a Sense of Touch," Nat. Mater., 15, 921–925, 2016.
49. Y. Zhuang, R. Li, M. Jiao, X. He, X. Gu and S. Huang "A flexible piezoresistive pressure sensor based on a perovskite MAPbBr3 nanocrystal-embedded polymer composite," Journal of material chemistry C issue 28, 10494-10503, Sep 2024.
50. H. Chung, J. Lee and W.Y. Lee "A Review: Marine Bio-Logging of Animal Behaviour and Ocean Environments," Ocean Sci. J., 56, 117–131, 2021.
51. T. Terada, K. Shiba, M. Suzuki, M. Sugita and H. lMatsubara "Film Sensor Using Carbon Particles for Monitoring Integrity of Steel Structures," in Proc. of the Smart Structures and Materials 2004: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, San Diego, CA, USA, 14–18 march 2004; 5391, 202–210.
52. J.J. Ku-Herrera and F. Aviles, "Cyclic tension and compression piezoresistivity of carbon nanotube/vinyl ester composites in the elastic and plastic regimes," Carbon, 50, 2592–2598, 2012.
53. W. Shun, Z. Zhiyue, G. Ke and Z. Hongping "Research progress of flexible piezoresistive strain sensing technology in structural health monitoring," Journal of building Structures 45, 242-261, Aug 2024