Recent Advances in Nanomaterial-Based Flexible Piezoresistive Sensors for Robotic Tactile Sensing

Si Won Park and Han Hee Jung*

Department of Information and Communication Engineering, Hannam University, Daejeon 34430, Republic of Korea

Abstract: The expansion of industrial automation has underscored the critical role of robotic systems, where pressure sensors serve as essential interfaces for tactile feedback and precise manipulation. Flexible piezoresistive pressure sensors have become especially attractive because of their simple design, straightforward operation, and scalable fabrication. Recent progress in conductive nanomaterials such as carbon- and metal-based fillers, and engineered microstructures, including surface and porous designs in both single and hierarchical configurations, has significantly improved sensor sensitivity and broadened their operational range, demonstrating how material choice and structural engineering directly shape device performance. This review introduces the underlying physics of piezoresistivity and discusses the metrics commonly used to characterize sensor behavior, including sensitivity, gauge factor, and response time, before examining advances in nanomaterial integration and structural strategies that enable enhanced functionality. Applications highlight their integration into robotic fingertips and joints, where they provide force regulation, object recognition, and motion tracking, underscoring their importance in robotic control. Remaining challenges such as uniformity, reproducibility, and large-scale manufacturability continue to hinder widespread adoption, yet ongoing improvements in material systems and fabrication methods promise to address these limitations. Through the integration of material design, structural engineering, and performance evaluation, this work establishes a comprehensive link between fundamental principles and robotic applications, offering insights that can guide the development of next-generation tactile sensing technologies and opening pathways toward next-generation robotic systems empowered by highly sensitive and reliable pressure sensors.

Keyword: Flexible, Piezoresistive, Pressure sensor, Robotic hands, Robotic gripper, Nanomaterial.

1. INTRODUCTION

Globally, the decline in the working-age population in aging societies has resulted in severe labor shortages, particularly in the manufacturing sector. Indeed, automation technologies have seen significantly greater adoption in countries experiencing more rapid population aging, and demographic aging accounts for nearly half of the cross-country differences in the adoption of robots and other automation technologies [1].

Consequently, industrial robots are increasingly being incorporated into modern manufacturing processes, leading to a heightened emphasis on research in this field [2]. As industrial automation advances toward more complex and adaptive operations, there is a rising demand for robots capable of perceiving and responding to subtle physical interactions in a manner similar to human tactile perception [3]. In this context, the ability to emulate not only the efficiency but also the dexterity of human labor has made tactile sensing a crucial capability for enabling robots to manipulate objects with human-like precision. Among various robotic systems, robotic hands have been specifically developed to replicate the functions of the human hand, and have long been studied to realize motor functions such as grasping and holding, as well as sensory functions including the exploration of texture, temperature, and humidity [4]. As a result of such research, robotic hands not only substitute for tasks traditionally performed by humans but also supplement them technologically, enabling their utilization across a wide range of industrial sectors. Examples include teleoperated precision surgery [5], multi-joint robots for process automation in automotive production lines [6], inspection robots for nuclear components developed in response to human radiation exposure limits [7], and semiconductor process robots employed in high-purity environments and repetitive tasks [8]. These applications provide advantages that are difficult for humans to achieve, such as continuous 24-hour operation, reduced cycle times, and improved productivity through greater manufacturing flexibility [9].

Current manufacturing demands are increasingly variable and call for the small-scale production of customized products, which requires robots with greater adaptability, flexibility, and advanced manipulation capabilities [10]. To meet these requirements, robotic hands must be able to perform complex tasks through precise force control and sensory feedback. This requires the quantitative detection of forces generated during contact with external objects, as well as the recognition of objects through tactile sensing. The integration of pressure sensors represents a viable solution to address these challenges.

*Address correspondence to this author at the Department of Information and Communication Engineering, Hannam University, Daejeon 34430, Republic of Korea; E-mail: hanheejung18@hnu.kr

Received on 30-09-2025 Accepted on 06-11-2025 Published on 08-11-2025

E-ISSN: 2409-9694/25

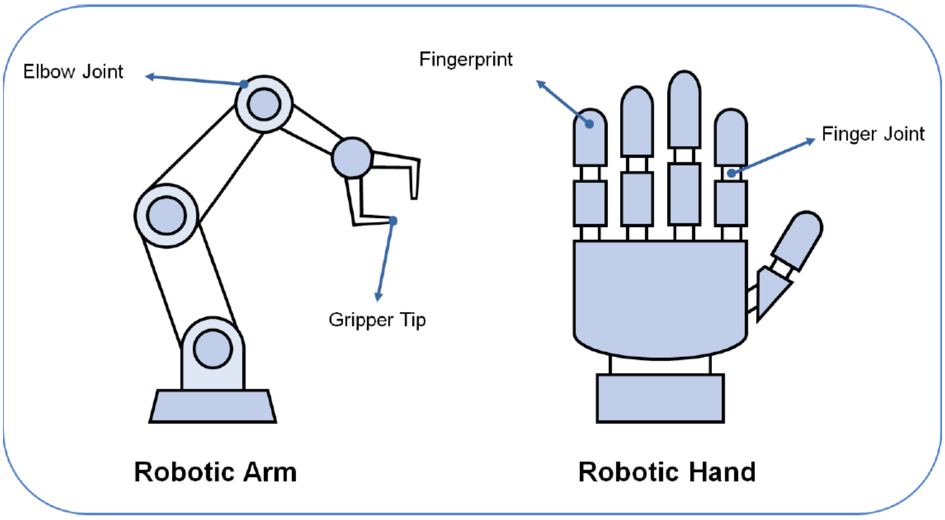

Figure 1: Representative locations for integrating flexible piezoresistive pressure sensors in robotics systems. Sensors positioned at joins (elbow or fingers) enable detection or angular motion and positional feedback, while those at gripper tips or fingerprint regions provide tactile information for object recognition and force regulation.

Tactile sensing in robotic hands can be achieved through pressure sensors, which measure object properties or contact events through physical contact between the sensor and the object [11]. As they convert external pressure into electrical signals, pressure sensors are particularly well suited for such tasks.

As demonstrated in Figure **1**, pressure sensors can be applied in two primary areas: joints [12, 13] and gripper tip or fingerprint regions [14, 15]. Sensors positioned at the joints are used to measure angles or positions through tension and compression, while those placed at the fingertip regions help recognize objects and regulate the gripping force of the robotic hand.

As described above, robotic hands can be fabricated in various forms depending on their intended applications, and therefore the use of flexible pressure sensors can be advantageous. Flexible pressure sensors exhibit excellent flexibility and ductility, enabling their use on complex curved surfaces and for detecting external stress signals [16]. These sensors can be designed with different mechanisms and structural configurations, among which the most prevalent are piezoresistive [17, 18], capacitive [19, 20], and piezoelectric [21, 22]. Capacitive sensors are noted for their high sensitivity and robustness but suffer from parasitic capacitance, while piezoelectric sensors are valued for their rapid response and operation without the need for an external power supply but are limited by their ability to respond only to dynamic signals [23-25]. To address these limitations, piezoresistive pressure sensors have been extensively studied, owing to their simple structure and operating principle, ease of fabrication, and cost-effectiveness [26]. Although they also exhibit drawbacks such as limited durability, non-linear response, stress relaxation, and hysteresis [27], these disadvantages are less critical than those of the other two types, making them a practical choice. Table **1** presents a summary of the advantages and disadvantages associated with each sensor type. This makes them suitable for use in various applications, including robotic hands. In addition to these practical advantages, ensuring uniformity and reproducibility during large-scale

Table 1: Comparison Table of Pressure Sensor Types

Mechanism	Working Principle	Signal Type	Advantage	Limitation
Piezoresistive	Change in electrical resistance due to deformation ($\Delta R/R$)	Resistive (voltage/current)	Simple structure and operating principle, ease of fabrication	Hysteresis, limited durability, non-linear response, stress relaxation
Capacitive	Change in capacitance due to variation in electrode distance or dielectric constant (ΔC)	Capacitive (charge/displacement current)	High robustness, high sensitivity	Parasitic capacitance
Piezoelectric	Generation of electric charge under mechanical stress	Voltage (AC signal)	Self-powered, rapid response, high sensitivity to dynamic pressure	Cannot detect static pressure

fabrication is another important issue that must be addressed. Subtle differences in nanomaterial dispersion, film morphology, or microstructural arrangement can lead to variations in sensor performance, indicating that process optimization is essential for achieving consistent and reliable behavior in flexible piezoresistive pressure sensors [28, 29].

The following sections provide a detailed discussion of the operating principles, materials, and configurations of flexible piezoresistive pressure sensors, followed by an overview of their application areas.

2. PIEZORESISTIVE PRESSURE SENSOR

Piezoresistive pressure sensors have emerged as a broadly compatible platform, offering simple architectures and versatile functionality across a wide spectrum of applications. In the sections that follow, we highlight the fundamental operating principles, key performance metrics, materials choices, structural engineering strategies, and representative domains of application.

2.1. Mechanism

Flexible piezoresistive pressure sensors are composed primarily of a composite material, which is created by adding conductive fillers to a non-conductive polymers [30]. The fundamental operating principle is to measure the piezoresistive response that arises from substrate deformation under external pressure. As demonstrated in Figure **2**, when deformation occurs in the substrate due to external pressure, the distribution and spacing between the fillers undergoes modification. This, in turn, induces the formation of conductive networks, thereby altering the electrical conductivity of the substrate.

The resistance change in a piezoresistive sensor can be expressed by the following equation.

$$R = \rho \frac{L}{A}$$

In this expression, R is the resistance measured in the sensor, ρ is the intrinsic resistivity of the constituent material, L is the effective path length of the conductive network, and A is its cross-sectional area [31].

The material utilized as the filler in pressure-resistant pressure sensors is primarily conductive nanomaterials, and these conductive nanomaterials form conductive networks through contact and the tunneling effect. These conductive nanomaterials form conductive networks through contact and the tunneling effect. In this context, the tunneling effect denotes the flow of current between two electrodes separated by a thin insulating barrier, which arises when the interparticle distance between adjacent conductive fillers becomes sufficiently small [32]. The phenomenon of conductive network formation is subsequently elucidated by percolation theory.

When the composite is deformed by external pressure, the conductive filler particles agglomerate and form conductive networks. This indicates a transition of the composite from an insulating to a conductive state, a phenomenon known as percolation [33]. The critical amount of filler required to establish continuous conductive networks and render the material conductive is referred to as the percolation threshold. Beyond this threshold, the electrical conductivity σ of the composite can be described by the following equation.

$$\sigma = \sigma_0 (P - P_c)^t$$

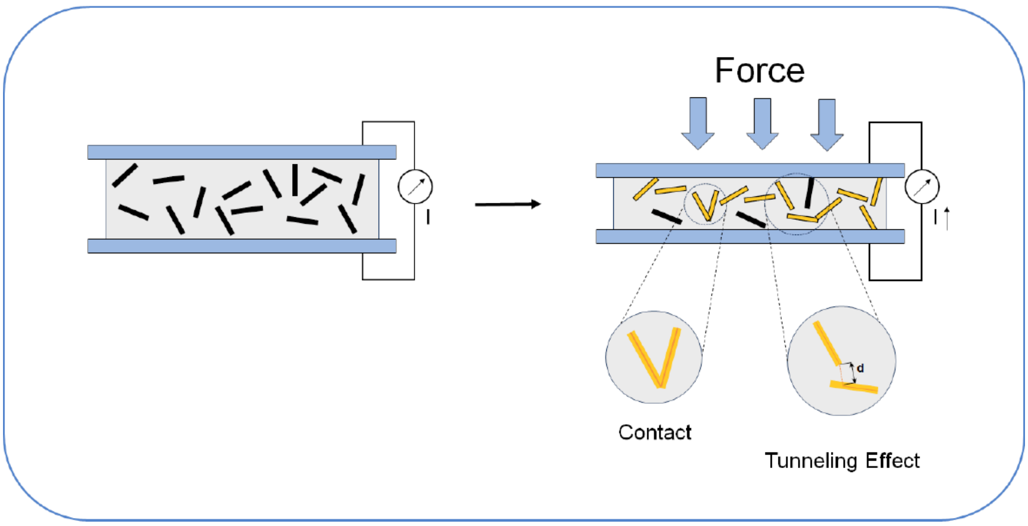

Figure 2: Principle of resistance generation in piezoresistive pressure sensor.

The equation, developed from the work of Kirkpatrick and Stauffer, defines Pc as the percolation threshold representing the probability of forming a conductive network, while P denotes the probability of the existence of a conductive phase corresponding to the volume fraction above the critical concentration; in addition, σ0 refers to the pre-factor and t represents the conductivity exponent, with P ≥ Pc indicating that the percolation threshold has been exceeded and a conductive network has been established [34]. The variation in the electrical conductivity of the composite can be interpreted in terms of changes in resistance, which underlies the operating principle of piezoresistive behavior.

2.2. Sensitivity

Sensitivity is a factor that indicates the objective performance of a pressure sensor. Sensors with high sensitivity can detect very small changes in pressure. In the linear region, the pressure sensitivity (S) of a piezoresistive sensor is expressed by the following equation.

$$\mathrm{S} = \frac{\Delta R/R_0}{\Delta P}$$

R is the relative change in the sensor resistance, and P is the applied pressure on the sensor [35]. From the above equation, it can be seen that sensitivity represents the intuitive change in resistance with respect to external pressure.

In addition, there exists a metric that is defined with respect to the deformation of the sensor rather than the applied external pressure. Since flexible piezoresistive pressure sensors can undergo various types of deformation, such as bending, stretching, and compression, the change in piezoresistance with respect to deformation must also be considered. This variation in piezoresistance relative to sensor deformation is expressed by the gauge factor (GF), which is defined by the following equation

$$\mathrm{GF} = \frac{\Delta R/R}{\varepsilon} = \frac{\Delta R/R}{\Delta l/l}$$

where ε denotes the strain of the sensor and R represents the piezoresistance [36]. Since GF characterizes the piezoresistive response with respect to overall strain, it may be interpreted or applied differently from sensitivity depending on the intended application. Both sensitivity and the gauge factor serve as key metrics for analyzing the pressure applied to the sensor, and in pressure sensing applications, accurate identification of the linear regions of these two metrics is required for proper sensor calibration.

2.3. Response Time

Response time is a characteristic observed in piezoresistive sensors, arising from the deformation of the sensor substrate under external pressure. It refers to the time required for the electrical signal to stabilize following deformation induced by an external stimulus [37]. The relaxation process, during which the sensor returns to its original state after the removal of the external stimulus, must also be considered, as it is closely associated with sensor performance. A shorter response time indicates enhanced dynamic sensing capability and the ability to detect instantaneous changes, while shorter relaxation times minimize unnecessary overshoot after stimulus removal, thereby improving accuracy.

Subsequently, Table **2** compares the sensitivity and response time of various piezoresistive pressure sensors composed of non-conductive polymers and conductive fillers.

Table 2: Sensing Range, Sensitivity, and Response Time by Material

Material	Sensitivity	Sensing Range	Response Time	Ref.
(MW)CNT-PDMS	$0.1661kPa^{-1}$(0-18 kPa) $0.4574kPa^{-1}$(18-133 kPa) $0.0989kPa^{-1}$(133-300 kPa)	0-300kPa	320ms	[38]
(SW)CNT-PDMS	$0.467kPa^{-1}$	0-5kPa	~10ms	[39]
MLG-PDMS	$0.23kPa^{-1}$	0-70kPa	N/A	[40]
CB/CNT-PDMS	$3.57kPa^{-1}$ (-21kPa)	0-275kPa	96ms	[41]
AgNW-PVDF	$0.014kPa^{-1}$(0-30kPa) $0.009kPa^{-1}$(30-100kPa)	0-100kPa	64ms	[42]
PVA/CNTs-PVDF	$0.0196kPa^{-1}$	0-40 kPa	~100ms	[43]
Graphene-PMMA	$7.42 \times 10^{-5}kPa^{-1}$	0-70kPa	~1ms	[44]

2.4. Material

Flexible piezoresistive pressure sensors, fabricated by incorporating conductive fillers into non-conductive substrates, rely heavily on the intrinsic properties of the materials to achieve flexibility and high sensitivity. Therefore, appropriately selecting and combining materials is crucial for fabricating pressure sensors capable of delivering the desired performance. Since the substrate forms the basis of a flexible pressure sensor, it must be mechanically flexible and stretchable, and it must be compatible with other materials for bonding or integration [27].

Materials that satisfy these requirements are usually elastomers, including polydimethylsiloxane (PDMS) [45, 46], polyurethane (PU) [47, 48], polymethylmeth-acrylate (PMMA) [49, 50], polyethylene terephthalate (PET) [51, 52], and polyimide (PI) [53, 54]. PDMS, a colorless, transparent elastomer, is one of the most commonly employed substrate materials for flexible pressure sensors due to its excellent physical, chemical, and thermal stability [55].

Since filler materials directly influence the generation of piezoresistivity and the variation of electrical signals in sensors, their selection must consider both the intrinsic electrical conductivity of the material and the percolation threshold, which is determined by the structure required to form conductive networks [33]. In addition, the electrical properties of pressure sensors can vary significantly depending on the morphology and concentration of the filler material, which must therefore be carefully considered [56]. Consequently, nanomaterials, such as carbon-based and metal-based substances, are widely adopted as fillers, and they are further classified as 0D, 1D, and 2D materials.

(1) 0D nanomaterials are particles whose dimensions remain entirely within the nanometer scale. Examples include carbon-based and metal-based nanoparticles, such as carbon black (CB) [57, 58] and metal nanoparticles. These fundamental materials are generally conductive, making them suitable candidates for use as fillers. Metal nanoparticles are typically composed of gold (Au) [59, 60] and silver (Ag) [61, 62].

(2) 1D nanomaterials possess aspect ratios ranging from the nanometer to the micrometer scale, with representative examples including carbon nanotubes (CNTs) [63, 64] and metal nanowires (NWs). These materials combine excellent mechanical strength with high electrical conductivity, and their ability to form network structures provides superior performance under expansion and contraction. CNTs can be categorized as single-walled (SWCNTs) or multi-walled (MWCNTs) depending on their structural characteristics, and further classified into aligned or random networks according to their arrangement [65]. Metal nanowires, typically composed of silver (Ag) [66, 67] or copper (Cu) [68, 69], are widely employed due to their high electrical conductivity.

(3) 2D nanomaterials possess micrometer-scale aspect ratios and nanometer-scale thicknesses, with graphene [70, 71] being a representative material. These films are composed of conductive thin films that possess excellent mechanical properties, characterized by high Young's modulus. Additionally, they exhibit remarkable compatibility. Structurally,

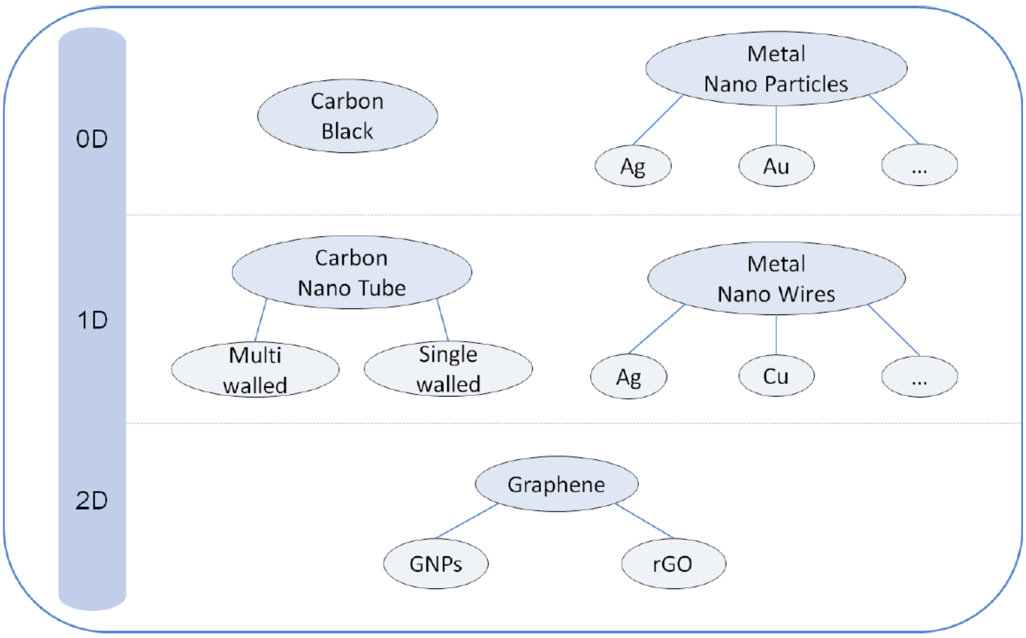

Figure 3: Representative conductive nanomaterials: Zero-, One-, and Two-Dimensional architectures.

graphene consists of a two-dimensional honeycomb lattice of carbon atoms, and its derivatives, such as graphene nanoplatelets (GNPs) [72, 73] and reduced graphene oxide (rGO) [74, 75], are also widely utilized.

In addition to these conventional nanomaterials, conductive polymers such as poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) [76, 77] have also been explored as alternative materials for flexible pressure sensors. PEDOT:PSS exhibits high flexibility, tunable electrical conductivity, and good compatibility with polymer matrices, allowing it to function as both a conductive filler and a stretchable electrode in hybrid composite systems [78]. These properties improve overall flexibility and stability while maintaining a percolation-based piezoresistive mechanism [79].

2.5. Structure

When the substrate of a pressure sensor is constructed in a planar form, it may experience reduced sensitivity and poor stability [80]. As illustrated in Figure **3**, substrate architectures are typically designed as either single structures or hierarchical structures. These architectures increase the contact area of conductive materials, thereby improving the sensitivity of the sensors.

A single structure comprises microstructures with uniform heights. This configuration provides the advantages of simple fabrication and low cost, while the uniformity of the microstructures ensures consistent pressure transmission and detection [81]. However, this design is limited by its low sensitivity and narrow pressure range [82].

A hierarchical structure comprises microstructures of different heights. In contrast to a single structure, the gradual increase in contact area under applied pressure enhances sensitivity. However, as the pressure continues to increase, deformation and stress within the existing contact areas result in reduced sensitivity and degraded linearity [83]. Furthermore, the incorporation of microstructures with varying heights enables more complex deformation behavior [84].

These substrate structures are designed based on specific requirements and objectives, and can be employed in either single-layer or double-layer configurations. Figure **4** illustrates the commonly used types in sequence.

(1) Surface microstructures

Surface microstructures provide a means of concentrating pressure through multiple structural features. In patterned microstructured substrates, pressure is concentrated on the protrusions, causing their contact area to increase rapidly even under small pressures. This results in significant changes in contact resistance, thereby enhancing the sensitivity of the sensor [85]. Various patterned structures are commonly employed, with pyramid-shaped [86, 87] and dome-shaped [88, 89] configurations being the most prevalent.

(2) Porous microstructures

Porous microstructures form conductive networks through the deformation of irregular pores within the material. When external pressure is applied, pore compression increases the number of conductive pathways. Due to the intrinsic voids within the material, the Young's modulus is reduced, which facilitates deformation under external pressure [90]. Sponge-like structures are generally preferred [91], and porous characteristics can be introduced either by directly employing inherently porous materials [92] or by creating porous architectures through the removal of internal constituents [93].

3. APPLICATION

Flexible piezoresistive pressure sensors have been extensively explored for deployment across a broad range of industrial applications. Their inherent flexibility

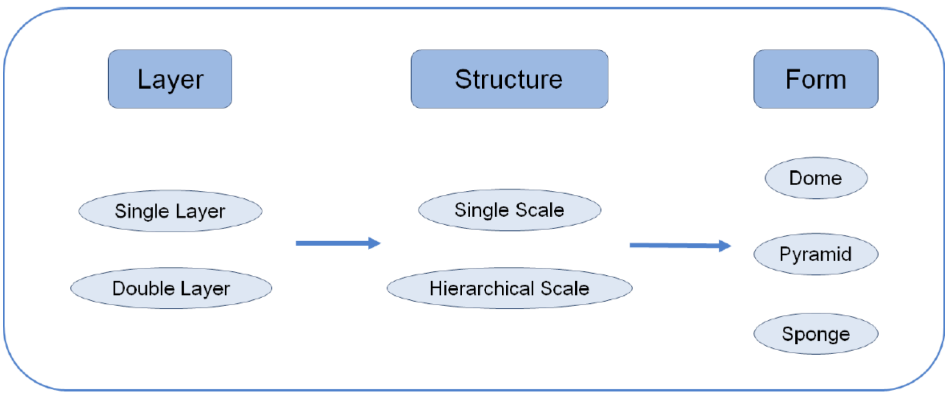

Figure 4: Structure design hierarchy of flexible piezoresistive pressure sensor.

and mechanical strength make them well-suited for applications on surfaces with diverse shapes, while their simple design facilitates easier manufacturing. These characteristics suggest that flexible piezoresistive pressure sensors could be utilized in automated processes of contemporary industrial factories, as well as in robotic hands and grippers that require precise movements during manufacturing.

Pei *et al*. fabricated a porous flexible piezoresistive pressure sensor using a light-curable flexible resin and graphene sheets, and demonstrated its applicability by integrating it onto the surface of a robotic finger to detect contact with objects. As shown in Figure **5**(**a**) the sensor fabrication process, where a linear range of 67.5% and a sensitivity of 2.64GF were measured in square pores. The pressure sensor, attached to the corresponding fingerprints in Figure **5**(**b**), is able to recognize the area where the picked-up object comes into contact with the surface. In Figure **5**(**c**), sensors 2 and 3, located at the positions where the finger touched the mug, detected pressure signals, resulting in an increase in resistance. These results indicate that flexible pressure sensors can effectively perceive grasped objects, as the porous and flexible structural design facilitates stable attachment to curved robotic surfaces and ensures consistent pressure sensing during motion and deformation.

Takeda *et al*. implemented a pressure sensor array with the structure shown in Figure **6**(**a**), consisting of a polyimide substrate, silver paste electrodes, and porous carbon ink, and applied it to a robotic arm/gripper control system. In this case, the conductive carbon ink was formulated from a mixture of PDMS, a deep eutectic solvent (DES), and CB. The system performs the function of picking up objects without causing damage by setting a threshold through communication with dedicated software. As illustrated in Figure **6**(**d**), the sensitivity of the sensor was demonstrated by monitoring resistance changes under applied pressures ranging from 0 to 5 N. By configuring the detection data via software to match the required threshold, the system can be used to pick up delicate objects like paper cups without damage, as demonstrated in Figure **6**(**b**). This performance was largely enabled by the combination of the porous carbon-based sensing layer and the flexible polyimide substrate, which together provided both high responsiveness and mechanical durability required for real-time force modulation in robotic grippers.

The above case demonstrates the application of

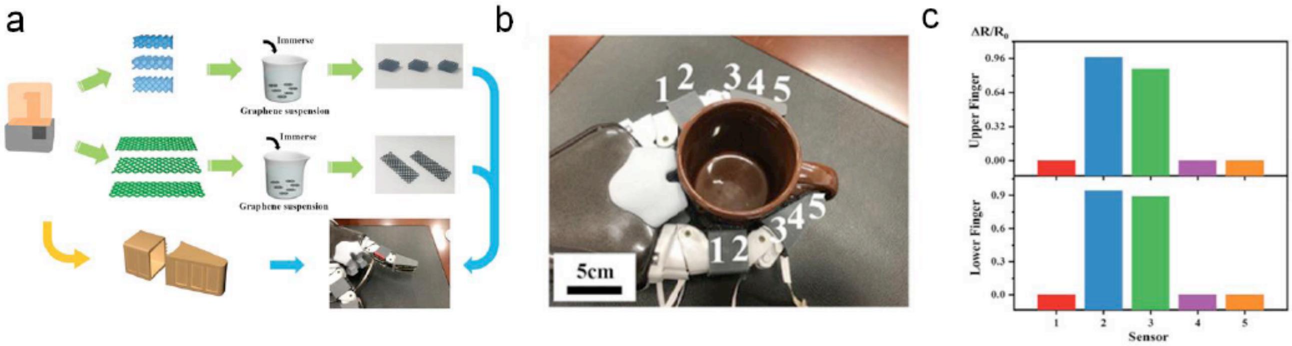

Figure 5: Flexible piezoresistive pressure sensors for robotics tactile sensing and control. (**a**) Fabrication process of a representative porous sensor. (**b**) Integration of sensors at fingertip positions. (**c**) Corresponding resistance changes during object contact [94].

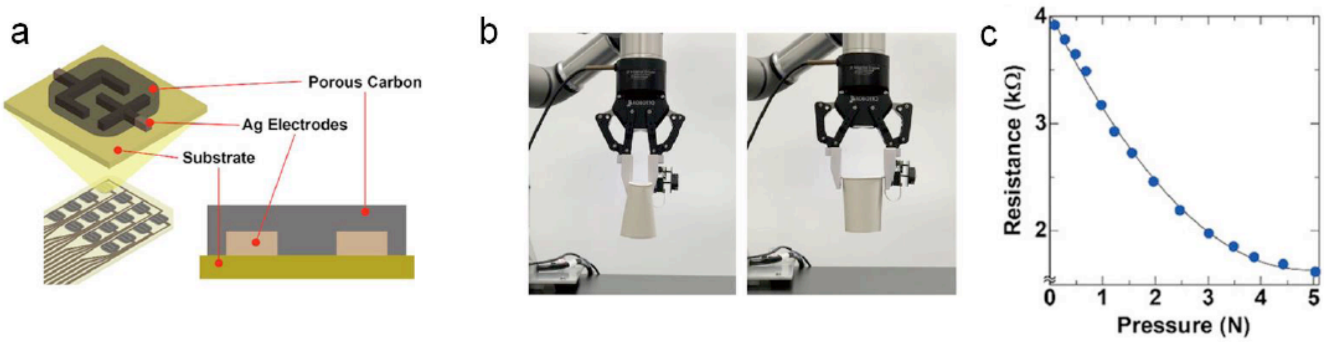

Figure 6: Flexible piezoresistive pressure sensors for robotics tactile sensing and control. (**a**) Device architecture of a printed sensor. (**b**) Gripping of a paper cup with force modulated by sensor feedback. (**c**) Resistance changes measured under applied forces of 0-5 N [95].

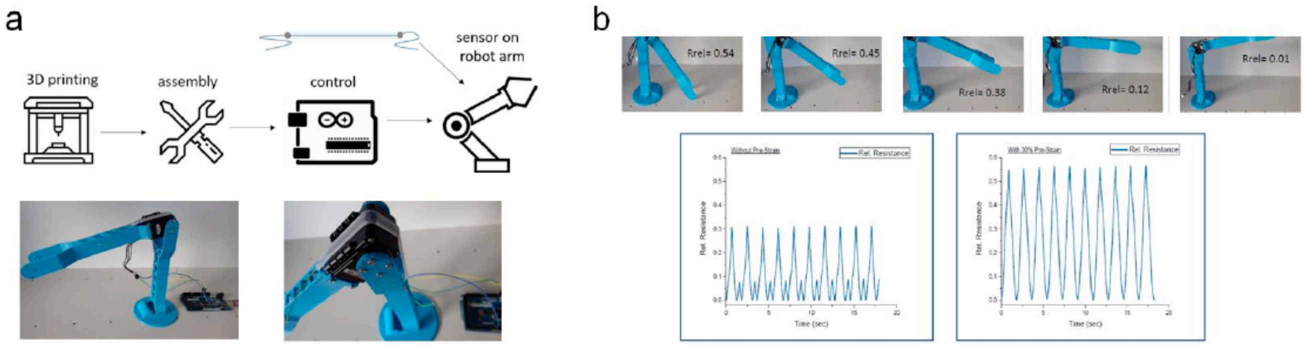

Figure 7: Piezoresistive pressure sensors for robotic tactile sensing and control. (**a**) Sensors integrated at the joints of a robotic arm to monitor angular displacement. (**b**) Resistance variations corresponding to changes in joint angle [96].

flexible pressure sensors at the contact interface with an object. In addition, they can also be attached to the joint regions corresponding to the elbow of a robotic arm, where they serve as position-monitoring sensors.

Georgopoulou *et al*. integrated carbon black (CB)-based sensor fibers into polydimethylsiloxane(PDMS) and EcoFlex to fabricate a flexible piezoresistive sensor with high tensile strength, which was attached to the joints of a robotic arm to determine its position and angle based on resistance changes. The PDMS- and EcoFlex-based sensors exhibit a gauge factor between 0 and 5 under deformations of 120% or less. Figure **7**(**b**) demonstrates that the sensor detected piezoresistive responses caused by tensile variations induced by changes in the joint angles of the robotic arm, thereby enabling the identification of positional information. In addition, repetitive operation over time confirmed the reliability and functionality of the data. This flexible fiber–elastomer composite architecture provides excellent stretchability and conformability, allowing the sensor to maintain stable signal output under continuous bending and extension, which are key requirements for reliable joint monitoring in dynamic robotic systems. Such positional information can help reduce errors in robotic arm movements.

4. CONCLUSION & INSIGHT

Flexible piezoresistive pressure sensors employed in robotic hands can capture information from pressures generated during the grasping of objects as well as from joint movements. Such data can be analyzed to enable functions such as regulating gripping force, determining joint angles, and identifying positions. However, most pressure sensors experience reduced sensitivity beyond their operational range, making it difficult to maintain linearity [97]. As a result, their use is limited in applications that require wide operational ranges or high forces. To address these challenges and improve both sensitivity and operating range, promising approaches include the use of suitable nanomaterials and the adoption of structural designs tailored to specific objectives.

The use of carbon- or metal-based nanomaterials, along with surface and porous microstructures that can be applied in either single or hierarchical configurations, promotes the formation of conductive networks and increases the contact area, thereby enabling high sensitivity and broad pressure ranges. Conductive nanomaterials provide superior conductivity, enhanced sensitivity through percolation, and excellent durability. As a result, they have become the key components of flexible piezoresistive pressure sensors currently under development.

This implies that research into the materials and structures employed in pressure sensors has a direct impact on improving their sensitivity and highlights the potential for further advancements. Future developments may involve the hybrid use of nanomaterials to harness the advantages of different dimensional materials, as well as the combination of various types of microstructures in the substrate to generate specific synergies that further enhance sensitivity. For instance, combining one-dimensional (1D) conductive fillers such as carbon nanotubes (CNTs) or silver nanowires (AgNWs) with two-dimensional (2D) materials like graphene could provide a well-balanced trade-off with respect to sensitivity, sensing range, and actuation displacement [98]. The 1D materials can form efficient conductive pathways, while the 2D materials enhance interfacial contact and structural integrity under repeated deformation. Moreover, integrating surface and porous microstructures within a hierarchical design may simultaneously achieve high sensitivity, large detection range, and stable pressure sensing, thereby enabling more reliable and multimodal tactile perception in robotic applications [99]. Taken together, these hybrid strategies highlight a shift in research focus from simply improving sensitivity to engineering multifunctional and scalable tactile systems that can operate reliably under complex mechanical conditions.

Nonetheless, the issue of uniformity in pressure sensors utilizing nanomaterials remains a critical challenge. Grain boundaries, film irregularities, material-handling difficulties, and particle agglomeration in solutions all contribute to reduced uniformity [100]. This presents a major obstacle to the mass production of flexible piezoresistive pressure sensors and may also raise concerns about manufacturing costs. Therefore, future efforts should focus on improving sensor uniformity through advances in fabrication processes while also reducing production costs and processing time. Such progress will be pivotal to the practical implementation of flexible piezoresistive sensors in large-scale robotic manufacturing. Furthermore, these scalable and cost-effective fabrication strategies may enable the deployment of flexible piezoresistive sensors beyond robotic hands, extending their applications to wearable devices, soft prosthetics, and intelligent manufacturing systems, thereby broadening their technological and industrial impact.

ACKNOWLEDGMENT

This work was supported by the 2025 Campus Innovation Project, funded by the Ministry of Education, in the Republic of Korea.

CONFLICTS OF INTEREST

The author declares no conflicts of interest.

REFERENCES

[1] Acemoglu, D., & Restrepo, P. (2022). Demographics and Automation. The Review of Economic Studies, 89(1), 1-44. https://doi.org/10.1093/restud/rdab031

[2] Ivanov, V., Andrusyshyn, V., Pavlenko, I., Pitel, Jan., & Bulej, V. (2024). New classification of industrial robotic gripping systems for sustainable production. Scientific Reports, 14(1), 295. https://doi.org/10.1038/s41598-023-50673-5

[3] Chi, C., Sun, X., Xue, N., Li, T., & Liu, C. (2018). Recent progress in technologies for tactile sensors. Sensors, 18(4), 948. https://doi.org/10.3390/s18040948

[4] Piazza, C., Grioli, G., Catalano, M. G., & Bicchi, A. (2019). A Century of Robotic Hands. Annual Review of Control, Robotics, and Autonomous Systems, 2, 1-32. https://doi.org/10.1146/annurev-control-060117-105003

[5] Diana, M., Marescaux, J., (2015). Robotic surgery. British Journal of Surgery, 102(2), e15-e28. https://doi.org/10.1002/bjs.9711

[6] Jiang, X., Koo, K. M., Kikuchi, K., Konno, A., & Uchiyama, M. (2011). Robotized Assembly of a Wire Harness in a Car Production Line. Advanced Robotics, 25(3-4), 473-489. https://doi.org/10.1163/016918610X551782

[7] Bogue, R. (2011). Robots in the nuclear industry: a review of technologies and applications. Industrial Robot, 38(2), 113-118. https://doi.org/10.1108/01439911111106327

[8] Weiss, A., Buchner, R., Tscheligi, M., & Fischer, H. (2011, May). Exploring human-robot cooperation possibilities for semiconductor manufacturing. In 2011 international conference on collaboration technologies and systems (CTS) (pp. 173-177). IEEE. https://doi.org/10.1109/CTS.2011.5928683

[9] Almurib, H. A., Al-Qrimli, H. F., & Kumar, N. (2012, January). A review of application industrial robotic design. In 2011 Ninth International Conference on ICT and Knowledge Engineering (pp. 105-112). IEEE. https://doi.org/10.1109/ICTKE.2012.6152387

[10] Kappassov, Z., Corrales, J. A., & Perdereau, V. (2015). Tactile sensing in dexterous robot hands. Robotics and Autonomous Systems, 74, 195-220. https://doi.org/10.1016/j.robot.2015.07.015

[11] Lee, M. H., & Nicholls, H. R. (1999). Review Article Tactile sensing for mechatronics—a state of the art survey. Mechatronics, 9(1), 1-31. https://doi.org/10.1016/S0957-4158(98)00045-2

[12] Mao, C., Jin, J., Mei, D., & Wang, Y. (2024). Development of Kirigami-Patterned Stretchable Tactile Sensor Array with Soft Hinges for Highly Sensitive Force Detection. Advanced Sensor Research, 3(8), 2400012. https://doi.org/10.1002/adsr.202400012

[13] Georgopoulou, A., Michel, S., & Clemens, F. (2021). Sensorized Robotic Skin Based on Piezoresistive Sensor Fiber Composites Produced with Injection Molding of Liquid Silicone. Polymers, 13(8), 1226. https://doi.org/10.3390/polym13081226

[14] Fonseca, G., Nunes-Pereira, J., & Silva, A. P. (2023). 3D Printed Robotic Hand with Piezoresistive Touch Capability. Applied Sciences, 13(14), 8002. https://doi.org/10.3390/app13148002

[15] Wang, S., Wang, X., Gao, Z., Zhang, Y., Wang, L., Liu, Y., Liu, J., Rong, L., Peng, Z., & Ouyang, Q. (2025). A smart finger for robotic tactile sensing of surface/subsurface patterns based on a high-density piezoresistive sensor array. Biosensors and Bioelectronics, 289, 117858. https://doi.org/10.1016/j.bios.2025.117858

[16] Chen, Y., Yan, X., Zhu, Y., Cui, M., Kong, L., Kuang, M., Zhang, X., & Wang, R. (2022). A carbon nanotube-based textile pressure sensor with high-temperature resistance. RSC Advances, 12(36), 23091-23098. http://doi.org/10.1039/D2RA04036K

[17] Gao, L., Zhu, C., Li, L., Zhang, C., Liu, J., Yu, H.-D., & Huang, W. (2019). All Paper-Based Flexible and Wearable Piezoresistive Pressure Sensor. ACS Applied Materials & Interfaces, 11(28), 25034-25042. https://doi.org/10.1021/acsami.9b07465

[18] Yao, J. L., Yang, X., Shao, N., Luo, H., Zhang, T., & Jiang, W. G. (2016). A flexible and highly sensitive piezoresistive pressure sensor based on micropatterned films coated with carbon nanotubes. Journal of Nanomaterials, 2016(1), 3024815. https://doi.org/10.1155/2016/3024815

[19] Mishra, R. B., El-Atab, N., Hussain, A. M., & Hussain, M. M. (2021). Recent Progress on Flexible Capacitive Pressure Sensors: From Design and Materials to Applications. Advanced Materials Technologies, 6(4), 2001023. https://doi.org/10.1002/admt.202001023

[20] Ha, K.-H., Huh, H., Li, Z., & Lu, N. (2022). Soft Capacitive Pressure Sensors: Trends, Challenges, and Perspectives. ACS Nano, 16(3), 3442-3448. https://doi.org/10.1021/acsnano.2c00308

[21] Yang, Y., Pan, H., Xie, G., Jiang, Y., Chen, C., Su, Y., Wang, Y., & Tai, H. (2020). Flexible piezoelectric pressure sensor based on polydopamine-modified BaTiO3/PVDF composite film for human motion monitoring. Sensors and Actuators A: Physical, 301, 111789. https://doi.org/10.1016/j.sna.2019.111789

[22] Zhi, C., Shi, S., Si, Y., Fei, B., Huang, H., & Hu, J. (2023). Recent Progress of Wearable Piezoelectric Pressure Sensors Based on Nanofibers, Yarns, and Their Fabrics via Electrospinning. Advanced Materials Technologies, 8(5), 2201161. https://doi.org/10.1002/admt.202201161

[23] Zhao, Y., Miao, L., Xiao, Y., & Sun, P. (2024). Research progress of flexible piezoresistive pressure sensor: A review. IEEE Sensors Journal. (pp. 31624-31644). IEEE. https://doi.org/10.1109/JSEN.2024.3443423

[24] Qiao, Z., Wei, A., Wang, K., Liu, Z., & Luo, N. (2022). Study of flexible piezoresistive sensors based on the hierarchical porous structure CNT /PDMS composite materials. Journal of Alloys and Compounds, 917, 165503. https://doi.org/10.1016/j.jallcom.2022.165503

[25] Yong, S., Chapman, J., & Aw, K. (2022). Soft and flexible large-strain piezoresistive sensors: On implementing proprioception, object classification and curvature estimation systems in adaptive, human-like robot hands. Sensors and Actuators A: Physical, 341, 113609. https://doi.org/10.1016/j.sna.2022.113609

[26] Chen, W., & Yan, X. (2020). Progress in achieving high-performance piezoresistive and capacitive flexible pressure sensors: A review. Journal of Materials Science & Technology, 43, 175-188. https://doi.org/10.1016/j.jmst.2019.11.010

[27] Seesaard, T., & Wongchoosuk, C. (2023). Flexible and Stretchable Pressure Sensors: From Basic Principles to State-of-the-Art Applications. Micromachines, 14(8), 1638. https://doi.org/10.3390/mi14081638

[28] Kanoun, O., Bouhamed, A., Ramalingame, R., Bautista-Quijano, J. R., Rajendran, D., & Al-Hamry, A. (2021). Review on conductive polymer/CNTs nanocomposites based flexible and stretchable strain and pressure sensors. Sensors, 21(2), 341. https://doi.org/10.3390/s21020341

[29] Ruth, S. R. A., Feig, V. R., Tran, H., & Bao, Z. (2020). Microengineering pressure sensor active layers for improved performance. Advanced Functional Materials, 30(39), 2003491. https://doi.org/10.1002/adfm.202003491

[30] Huang, Y., Fan, X., Chen, S.-C., & Zhao, N. (2019). Emerging Technologies of Flexible Pressure Sensors: Materials, Modeling, Devices, and Manufacturing. Advanced Functional Materials, 29(12), 1808509. https://doi.org/10.1002/adfm.201808509

[31] del Bosque, A., Sánchez-Romate, X. F., Sánchez, M., & Ureña, A. (2024). Toward flexible piezoresistive strain sensors based on polymer nanocomposites: a review on fundamentals, performance, and applications. Nanotechnology, 35(29), 292003. https://doi.org/10.1088/1361-6528/ad3e87

[32] Wang, L., & Li, Y. (2013). A Review for Conductive Polymer Piezoresistive Composites and a Development of a Compliant Pressure Transducer. IEEE Transactions on Instrumentation and Measurement, 62(2), 495-502. https://doi.org/10.1109/TIM.2012.2215160

[33] Cravanzola, S., Haznedar, G., Scarano, D., Zecchina, A., & Cesano, F. (2013). Carbon-based piezoresistive polymer composites: Structure and electrical properties. Carbon, 62, 270-277. https://doi.org/10.1016/j.carbon.2013.05.064

[34] Zhang, W., Dehghani-Sanij, A. A., & Blackburn, R. S. (2007). Carbon based conductive polymer composites. Journal of Materials Science, 42(10), 3408-3418. https://doi.org/10.1007/s10853-007-1688-5

[35] Park, J., Lee, Y., Hong, J., Ha, M., Jung, Y.-D., Lim, H., Kim, S. Y., & Ko, H. (2014). Giant tunneling piezoresistance of composite elastomers with interlocked microdome arrays for ultrasensitive and multimodal electronic skins. ACS Nano, 8(5), 4689-697. https://doi.org/10.1021/nn500441k

[36] Chung, D. D. L. (2020). A critical review of piezoresistivity and its application in electrical-resistance-based strain sensing. Journal of Materials Science, 55(32), 15367-15396. https://doi.org/10.1007/s10853-020-05099-z

[37] Shu, Q., Pang, Y., Li, Q., Gu, Y., Liu, Z., Liu, B., Li, J., & Li, Y. (2024). Flexible resistive tactile pressure sensors. Journal of Materials Chemistry A, 12(16), 9296-9321. https://doi.org/10.1039/d3ta06976a

[38] Zhao, Y., Shen, T., Zhang, M., Yin, R., Zheng, Y., Liu, H., Sun, H., Liu, C., & Shen, C. (2023). Advancing the pressure sensing performance of conductive CNT/PDMS composite film by constructing a hierarchical-structured surface. Nano Materials Science, 5(4), 343-350. https://doi.org/10.1016/j.nanoms.2021.10.002

[39] Tai, Y.-L., & Yang, Z.-G. (2015). Flexible pressure sensing film based on ultrasensitive SWCNT/PDMS spheres for monitoring human pulse signals. Journal of Materials Chemistry B, 3(27), 5436-5441. https://doi.org/10.1039/C5TB00653H

[40] Rinaldi, A., Tamburrano, A., Fortunato, M., & Sarto, M. S. (2016). A Flexible and Highly Sensitive Pressure Sensor Based on a PDMS Foam Coated with Graphene Nanoplatelets. Sensors, 16(12), 2148. https://doi.org/10.3390/s16122148

[41] Yuan, J., Li, Q., Ding, L., Shi, C., Wang, Q., Niu, Y., & Xu, C. (2022). Carbon Black/Multi-Walled Carbon Nanotube-Based, Highly Sensitive, Flexible Pressure Sensor. ACS Omega, 7(48), 44428-44437. https://doi.org/10.1021/acsomega.2c06548

[42] Jing, M., Zhou, J., Zhang, P., Hou, D., Shen, J., Tian, J., & Chen, W. (2022). Porous AgNWs/Poly(vinylidene fluoride) Composite-Based Flexible Piezoresistive Sensor with High Sensitivity and Wide Pressure Ranges. ACS Applied Materials & Interfaces, 14(49), 55119-55129. https://doi.org/10.1021/acsami.2c17879

[43] Zhou, Q., Chen, T., Cao, S., Xia, X., Bi, Y., & Xiao, X. (2021). A novel flexible piezoresistive pressure sensor based on PVDF/PVA-CNTs electrospun composite film. Applied Physics A, 127(9), 667. https://doi.org/10.1007/s00339-021-04797-y

[44] Liu, Y., Zhang, Y., Lin, X., Lv, K.-h., Yang, P., Qiu, J., & Liu, G.-j. (2020). Improved High-Yield PMMA/Graphene Pressure Sensor and Sealed Gas Effect Analysis. Micromachines, 11(9), 786. https://doi.org/10.3390/mi11090786

[45] Long, Z., Liu, X., Xu, J., Huang, Y., & Wang, Z. (2022). High-Sensitivity Flexible Piezoresistive Pressure Sensor Using PDMS/MWNTS Nanocomposite Membrane Reinforced with Isopropanol for Pulse Detection. Sensors, 22(13), 4765. https://doi.org/10.3390/s22134765

[46] Niu, D., Jiang, W., Ye, G., Wang, K., Yin, L., Shi, Y., Chen, B., Luo, F., & Liu, H. (2018). Graphene-elastomer nanocomposites based flexible piezoresistive sensors for strain and pressure detection. Materials Research Bulletin, 102, 92-99. https://doi.org/10.1016/j.materresbull.2018.02.005

[47] Tewari, A., Gandla, S., Bohm, S., McNeill, C. R., & Gupta, D. (2018). Highly exfoliated MWNT-rGO ink-wrapped polyurethane foam for piezoresistive pressure sensor applications. ACS applied materials & interfaces, 10(6), 5185-5195. https://doi.org/10.1021/acsami.7b15252

[48] Tung, T. T., Robert, C., Castro, M., Feller, J. F., Kim, T. Y., & Suh, K. S. (2016). Enhancing the sensitivity of graphene/polyurethane nanocomposite flexible piezo-resistive pressure sensors with magnetite nano-spacers. Carbon, 108, 450-460. https://doi.org/10.1016/j.carbon.2016.07.018

[49] Wagner, S., Yim, C., McEvoy, N., Kataria, S., Yokaribas, V., Kuc, A., Pindl, S., Fritzen, C.-P., Heine, T., Duesberg, G. S., & Lemme, M. C. (2018). Highly sensitive electromechanical piezoresistive pressure sensors based on large-area layered PtSe2 films. Nano letters, 18(6), 3738-3745. https://doi.org/10.1021/acs.nanolett.8b00928

[50] Chen, D., Liu, Z., Li, Y., Sun, D., Liu, X., Pang, J., ... & Zhou, W. (2020). Unsymmetrical alveolate PMMA/MWCNT film as a piezoresistive E-skin with four-dimensional resolution and application for detecting motion direction and airflow rate. ACS Applied Materials & Interfaces, 12(27), 30896-30904. https://doi.org/10.1021/acsami.0c02640

[51] Zhao, W., Natsuki, J., Trung, V. D., Li, H., Tan, J., Yang, W., & Natsuki, T. (2024). AgNPs/CNTs modified nonwoven fabric for PET-based flexible interdigitated electrodes in pressure sensor applications. Chemical Engineering Journal, 499, 156252. https://doi.org/10.1016/j.cej.2024.156252

[52] Balderrama, V. S., Leon-Gil, J. A., Fernández-Benavides, D. A., Ponce-Hernández, J., & Bandala-Sánchez, M. (2021). MEMS piezoresistive pressure sensor based on flexible PET thin-film for applications in gaseous-environments. IEEE Sensors Journal, 22(3), https://doi.org/1939-1947. 10.1109/JSEN.2021.3135543

[53] Zhu, Y., Jiang, S., Xiao, Y., Yu, J., Sun, L., & Zhang, W. (2018). A flexible three-dimensional force sensor based on PI piezoresistive film. Journal of Materials Science: Materials in Electronics, 29(23), 19830-19839. https://doi.org/10.1007/s10854-018-0111-0

[54] Li, Q., Luo, S., & Wang, Q. M. (2019). Piezoresistive thin film pressure sensor based on carbon nanotube-polyimide nanocomposites. Sensors and Actuators A: Physical, 295, 336-342. https://doi.org/10.1016/j.sna.2019.06.017

[55] Zhang, X., Li, N., Wang, G., Zhang, C., Zhang, Y., Zeng, F., Liu, H., Yi, G., & Wang, Z. (2023). Research status of polysiloxane-based piezoresistive flexible human electronic sensors. RSC advances, 13(24), 16693-16711. https://doi.org/10.1039/D3RA03258B

[56] Yoo, J., Kim, D.-Y., Kim, H., Hur, O.-N., & Park, S.-H. (2022). Comparison of Pressure Sensing Properties of Carbon Nanotubes and Carbon Black Polymer Composites. Materials, 15(3), 1213. https://doi.org/10.3390/ma15031213

[57] Cao, M., Fan, S., Qiu, H., Su, D., Li, L., & Su, J. (2020). CB nanoparticles optimized 3D wearable graphene multifunctional piezoresistive sensor framed by loofah sponge. ACS applied materials & interfaces, 12(32), 36540-36547. https://doi.org/10.1021/acsami.0c09813

[58] Devaraj, H., Yellapantula, K., Stratta, M., McDaid, A., & Aw, K. (2019). Embedded piezoresistive pressure sensitive pillars from piezoresistive carbon black composites towards a soft large-strain compressive load sensor. Sensors and Actuators A: Physical, 285, 645-651. https://doi.org/10.1016/j.sna.2018.12.006

[59] Karmakar, R. S., Lu, Y.-J., Fu, Y., Wei, K.-C., Chan, S.-H., Wu, M.-C., Lee, J.-W., Lin, T.-K., & Wang, J.-C. (2017). Cross-talk immunity of PEDOT: PSS pressure sensing arrays with gold nanoparticle incorporation. Scientific reports, 7(1), 12252. https://doi.org/10.1038/s41598-017-12420-5

[60] Wang, J., Zhang, C., Chen, D., Sun, M., Liang, N., Cheng, Q., Ji, Y., Gao, H., Guo, Z., Li, Y., Sun, D., Li, Q., & Liu, H. (2020). Fabrication of a sensitive strain and pressure sensor from gold nanoparticle-assembled 3D-interconnected graphene microchannel-embedded PDMS. ACS Applied Materials & Interfaces, 12(46), 51854-51863. https://doi.org/10.1021/acsami.0c16152

[61] Chen, B., Li, H., Zhang, S., Lai, X., Zeng, X., Wu, X., Cheng, X., & Liu, H. (2022). High-performance and superhydrophobic piezoresistive pressure sensor based on mountain ridge-like microstructure by silver nanoparticles and reduced graphene oxide. Composites Part A: Applied Science and Manufacturing, 162, 107171. https://doi.org/10.1016/j.compositesa.2022.107171

[62] Han, X., Lv, Z., Ran, F., Dai, L., Li, C., & Si, C. (2021). Green and stable piezoresistive pressure sensor based on lignin-silver hybrid nanoparticles/polyvinyl alcohol hydrogel. International Journal of Biological Macromolecules, 176, 78-86. https://doi.org/10.1016/j.ijbiomac.2021.02.055

[63] Oh, J., Kim, D.-Y., Kim, H., Hur, O.-N., & Park, S.-H. (2022). Comparative Study of Carbon Nanotube Composites as Capacitive and Piezoresistive Pressure Sensors under Varying Conditions. Materials, 15(21), 7637. https://doi.org/10.3390/ma15217637

[64] Hwang, J., Jang, J., Hong, K., Kim, K. N., Han, J. H., Shin, K., & Park, C. E. (2011). Poly (3-hexylthiophene) wrapped carbon nanotube/poly (dimethylsiloxane) composites for use in finger-sensing piezoresistive pressure sensors. Carbon, 49(1), 106-110. https://doi.org/10.1016/j.carbon.2010.08.048

[65] Park, J., Hwang, J. C., Kim, G. G., & Park, J. U. (2020). Flexible electronics based on one-dimensional and two-dimensional hybrid nanomaterials. InfoMat, 2(1), 33-56. https://doi.org/10.1002/inf2.12047

[66] Cai, B., Wang, L., Yu, F., Jia, J., Li, J., Li, X., Yang, X., Jiang, Y., & Lü, W. (2022). Compressible piezoresistive pressure sensor based on Ag nanowires wrapped conductive carbonized melamine foam. Applied Physics A, 128(1), 6. https://doi.org/10.1007/s00339-021-05143-y

[67] Liu, W. C., & Watt, A. A. (2021). Solvodynamically printed silver nanowire/ethylene-co-vinyl acetate composite films as sensitive piezoresistive pressure sensors. ACS Applied Nano Materials, 4(8), 7905-7916. https://doi.org/10.1021/acsanm.1c01229

[68] Xu, X., Wang, R., Nie, P., Cheng, Y., Lu, X., Shi, L., & Sun, J. (2017). Copper nanowire-based aerogel with tunable pore structure and its application as flexible pressure sensor. ACS applied materials & interfaces, 9(16), 14273-14280. https://doi.org/10.1021/acsami.7b02087

[69] Zhu, Y., Hartel, M. C., Yu, N., Garrido, P. R., Kim, S., Lee, J., Bandaru, P., Guan, S., Lin, H., Emaminejad, S., de Barros, N. R., Ahadian, S., Kim, H.-J., Sun, W., Jucaud, V., Dokmeci, M. R., Weiss, P. S., Yan, R., & Khademhosseini, A. (2022). Epidermis-inspired wearable piezoresistive pressure sensors using reduced graphene oxide self-wrapped copper nanowire networks. Small Methods, 6(1), 2100900. https://doi.org/10.1002/smtd.202100900

[70] Jing, Z., Zhang, Q., Cheng, Y., Ji, C., Zhao, D., Liu, Y., Jia, W., Pan, S., & Sang, S. (2020). Highly sensitive, reliable and flexible piezoresistive pressure sensors based on graphene-PDMS@ sponge. Journal of Micromechanics and Microengineering, 30(8), 085012. https://doi.org/10.1088/1361-6439/ab948f

[71] Liu, W., Liu, N., Yue, Y., Rao, J., Cheng, F., Su, J., Liu, Z., & Gao, Y. (2018). Piezoresistive pressure sensor based on synergistical innerconnect polyvinyl alcohol nanowires/wrinkled graphene film. Small, 14(15), 1704149. https://doi.org/10.1002/smll.201704149

[72] Kwon, S. N., Kim, S. W., Kim, I. G., Hong, Y. K., & Na, S. I. (2019). Direct 3D Printing of graphene nanoplatelet/silver nanoparticle-based nanocomposites for multiaxial piezoresistive sensor applications. Advanced Materials Technologies, 4(2), 1800500. https://doi.org/10.1002/admt.201800500

[73] Azam, M. U., Schiffer, A., & Kumar, S. (2024). Mechanical and piezoresistive properties of GNP/UHMWPE composites and their cellular structures manufactured via selective laser sintering. Journal of Materials Research and Technology, 28, 1359-1369. https://doi.org/10.1016/j.jmrt.2023.12.089

[74] Bhatt, B. B., Kumar, L., Kushwaha, A., & Gupta, D. (2021). An ultra-compressible piezoresistive strain and pressure sensor based on RGO-CNT-Melamine foam composite for biomedical sensing. Sensors and Actuators A: Physical, 331, 112875. https://doi.org/10.1016/j.sna.2021.112875

[75] Wu, J., Li, H., Lai, X., Chen, Z., & Zeng, X. (2020). Conductive and superhydrophobic F-rGO@ CNTs/chitosan aerogel for piezoresistive pressure sensor. Chemical Engineering Journal, 386, 123998. https://doi.org/10.1016/j.cej.2019.123998

[76] Zhang, X., Yang, W., Zhang, H., Xie, M., & Duan, X. (2021). PEDOT: PSS: From conductive polymers to sensors. Nanotechnology and Precision Engineering, 4(4). https://doi.org/10.1063/10.0006866

[77] Wang, J. C., Karmakar, R. S., Lu, Y. J., Huang, C. Y., & Wei, K. C. (2015). Characterization of piezoresistive PEDOT: PSS pressure sensors with inter-digitated and cross-point electrode structures. Sensors, 15(1), 818-831. https://doi.org/10.3390/s150100818

[78] Fan, X., Nie, W., Tsai, H., Wang, N., Huang, H., Cheng, Y., ... & Xia, Y. (2019). PEDOT: PSS for flexible and stretchable electronics: modifications, strategies, and applications. Advanced Science, 6(19), 1900813. https://doi.org/10.1002/advs.201900813

[79] Trifigny, N., Kelly, F. M., Cochrane, C., Boussu, F., Koncar, V., & Soulat, D. (2013). PEDOT: PSS-based piezo-resistive sensors applied to reinforcement glass fibres for in situ measurement during the composite material weaving process. Sensors, 13(8), 10749-10764. https://doi.org/10.3390/s130810749

[80] Dai, S.-W., Gu, Y.-L., Wu, Y.-X., Shen, S.-C., Zhang, C., Kong, T.-T., Li, Y.-T., Gong, L.-X., Zhang, G.-D., Zhao, L., & Tang, L.-C. (2021). Bamboo-inspired mechanically flexible and electrically conductive polydimethylsiloxane foam materials with designed hierarchical pore structures for ultra-sensitive and reliable piezoresistive pressure sensor. Composites Part B: Engineering, 225, 109243. https://doi.org/10.1016/j.compositesb.2021.109243

[81] Zong, X., Zhang, N., Ma, X., Wang, J., & Zhang, C. (2025). Polymer-based flexible piezoresistive pressure sensors based on various micro/nanostructures array. Composites Part A: Applied Science and Manufacturing, 190, 108648. https://doi.org/10.1016/j.compositesa.2024.108648

[82] Baek, J., Shan, Y., Mylvaganan, M., Zhang, Y., Yang, X., Qin, F., Zhao, K., Song, H. W., Mao, H., & Lee, S. (2023). Mold-Free Manufacturing of Highly Sensitive and Fast-Response Pressure Sensors Through High-Resolution 3D Printing and Conformal Oxidative Chemical Vapor Deposition Polymers. Advanced Materials, 35(41), 2304070. https://doi.org/10.1002/adma.202304070

[83] Shi, J., Wang, L., Dai, Z., Zhao, L., Du, M., Li, H., & Fang, Y. (2018). Multiscale hierarchical design of a flexible piezoresistive pressure sensor with high sensitivity and wide linearity range. Small, 14(27), 1800819. https://doi.org/10.1002/smll.201800819

[84] Li, G., Chen, D., Li, C., Liu, W., & Liu, H. (2020). Engineered microstructure derived hierarchical deformation of flexible pressure sensor induces a supersensitive piezoresistive property in broad pressure range. Advanced Science, 7(18), 2000154. https://doi.org/10.1002/advs.202000154

[85] Li, W., Jin, X., Han, X., Li, Y., Wang, W., Lin, T., & Zhu, Z. (2021). Synergy of porous structure and microstructure in piezoresistive material for high-performance and flexible pressure sensors. ACS applied materials & interfaces, 13(16), 19211-19220. https://doi.org/10.1021/acsami.0c22938

[86] Zhang, Y. X., He, Y., Liang, Y., Tang, J., Yang, Y., Song, H. M., ... & Chen, Y. M. (2023). Sensitive piezoresistive pressure sensor based on micropyramid patterned tough hydrogel. Applied Surface Science, 615, 156328. https://doi.org/10.1016/j.apsusc.2023.156328

[87] Yang, J. C., Kim, J.-O., Oh, J., Kwon, S. Y., Sim, J. Y., Kim, D. W., Choi, H. B., & Park, S. (2019). Microstructured porous pyramid-based ultrahigh sensitive pressure sensor insensitive to strain and temperature. ACS applied materials & interfaces, 11(21), 19472-19480. https://doi.org/10.1021/acsami.9b03261

[88] Hong, S. H., Chen, T., Wang, G., Popovic, S. M., Filleter, T., & Naguib, H. E. (2023). Room-temperature self-healing polysiloxane networks for highly sensitive piezoresistive pressure sensor with microdome structures. Chemical Engineering Journal, 471, 144429. https://doi.org/10.1016/j.cej.2023.144429

[89] Li, J., Wu, T., Jiang, H., Chen, Y., & Yang, Q. (2021). Ultrasensitive hierarchical piezoresistive pressure sensor for wide-range pressure detection. Advanced Intelligent Systems, 3(11), 2100070. https://doi.org/10.1002/aisy.202100070

[90] Zhao, T., Li, T., Chen, L., Yuan, L., Li, X., & Zhang, J. (2019). Highly sensitive flexible piezoresistive pressure sensor developed using biomimetically textured porous materials. ACS applied materials & interfaces, 11(32), 29466-29473. https://doi.org/10.1021/acsami.9b09265

[91] Cao, W., Luo, Y., Dai, Y., Wang, X., Wu, K., Lin, H., Rui, K., & Zhu, J. (2023). Piezoresistive pressure sensor based on a conductive 3D sponge network for motion sensing and human-machine interface. ACS Applied Materials & Interfaces, 15(2), 3131-3140. https://doi.org/10.1021/acsami.2c18203

[92] Li, X., Li, X., Liu, T., Lu, Y., Shang, C., Ding, X., Zhang, J., Feng, Y., & Xu, F.-J. (2021). Wearable, washable, and highly sensitive piezoresistive pressure sensor based on a 3D sponge network for real-time monitoring human body activities. ACS Applied Materials & Interfaces, 13(39), 46848-46857. https://doi.org/10.1021/acsami.1c09975

[93] Oh, J., Kim, J.-O., Kim, Y., Choi, H. B., Yang, J. C., Lee, S., Pyatykh, M., Kim, J., Sim, J. Y., & Park, S. (2019). Highly uniform and low hysteresis piezoresistive pressure sensors based on chemical grafting of polypyrrole on elastomer template with uniform pore size. Small, 15(33), 1901744. https://doi.org/10.1002/smll.201901744

[94] Pei, Z., Zhang, Q., Yang, K., Yuan, Z., Zhang, W., & Sang, S. (2021). A fully 3D-printed wearable piezoresistive strain and tactile sensing array for robot hand. Advanced Materials Technologies, 6(7), 2100038. https://doi.org/10.1002/admt.202100038

[95] Takeda, Y., Wang, Y. F., Yoshida, A., Sekine, T., Kumaki, D., & Tokito, S. (2024). Advancing robotic gripper control with the integration of flexible printed pressure sensors. Advanced Engineering Materials, 26(9), 2302031. https://doi.org/10.1002/adem.202302031

[96] Georgopoulou, A., Michel, S., Vanderborght, B., & Clemens, F. (2021). Piezoresistive sensor fiber composites based on silicone elastomers for the monitoring of the position of a robot arm. Sensors and Actuators A: Physical, 318, 112433. https://doi.org/10.1016/j.sna.2020.112433

[97] Xu, S., Xu, Z., Li, D., Cui, T., Li, X., Yang, Y., Liu, H., & Ren, T. (2023). Recent Advances in Flexible Piezoresistive Arrays: Materials, Design, and Applications. Polymers, 15(12), 2699. https://doi.org/10.3390/polym15122699

[98] Pyo, S., Eun, Y., Sim, J., Kim, K., & Choi, J. (2022). Carbon nanotube-graphene hybrids for soft electronics, sensors, and actuators. Micro and Nano Systems Letters, 10(1), 9. https://doi.org/10.1186/s40486-022-00151-w

[99] Li, W., Jin, X., Han, X., Li, Y., Wang, W., Lin, T., & Zhu, Z. (2021). Synergy of porous structure and microstructure in piezoresistive material for high-performance and flexible pressure sensors. ACS applied materials & interfaces, 13(16), 19211-19220. https://doi.org/10.1021/acsami.0c22938

[100] Kim, J. S., So, Y., Lee, S., Pang, C., Park, W., & Chun, S. (2021). Uniform pressure responses for nanomaterials-based biological on-skin flexible pressure sensor array. Carbon, 181, 169-176. https://doi.org/10.1016/j.carbon.2021.04.096

https://doi.org/10.31875/2409-9694.2025.12.06