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Flexible Pressure Sensors Based on Three-dimensional Structure for High Sensitivity

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Abstract

The importance of flexible polymer-based pressure sensors is growing in fields like healthcare monitoring, tactile recognition, gesture recognition, human-machine interface, and robot skin. In particular, health monitoring and tactile devices require high sensor sensitivity. Researchers have worked on sensor material and structure to achieve high sensitivity. A simple and effective method has been to employ three-dimensional pressure sensors. Three-dimensional (3D) structures dramatically increase sensor sensitivity by achieving larger local deformations for the same pressure. In this paper, the performance, manufacturing method, material, and structure of high-sensitivity flexible pressure sensors based on 3D structures, are reviewed.

Keywords: Flexible pressure sensors, Three-dimensional structure, High sensitivity, Healthcare monitoring, Motion recognition, Human-machine interface

1. INTRODUCTION

Flexible pressure sensors are attracting attention in fields like healthcare monitoring, gesture sensors, tactile sensors, human machine interfaces, and robot skins due to unique properties like flexibility, lightness, high sensitivity, and ease of fabrication [1-7]. In daily life too, applications such as pulse monitoring, finger movement, soft touch, and foot pressure measurement require recognition with high sensitivity in the low pressure (0–10 kPa) and medium pressure (10–100 kPa) regions [8]. According to the sensing mechanism, pressure sensors are divided into three types—piezoresistive [9,10], piezocapacitive [11,12], and piezoelectric [13,14]. Recently, ultra-sensitive sensors based on triboelectricity have also been introduced [15-18]. In piezoresistive pressure sensors, a physical stimulus changes the contact area between two electrodes, which changes the resistance, and therefore the current between the two electrodes. Although piezoresistive sensors have disadvantages such as sensitivity to temperature, they are widely used in flexible pressure sensors due to advantages such as relatively easy operation, high sensing sensitivity, simple structure, and fast response. In the piezocapacitive method, the distance between the two electrodes changes according to a physical stimulus and the pressure is measured by recognizing the change in the dielectric constant between the two electrodes. Piezocapacitive pressure sensors have advantages such as ease of fabrication, low hysteresis, and high stability. However, the relative complexity and noise of signal acquisition are disadvantages of piezocapacitive sensors. Piezoelectric pressure sensors work by converting mechanical energy into electrical energy. Since the performance of piezoelectric sensors is dependent on intrinsic material properties rather than the spatial change relative to pressure, this paper focuses on piezoresistive and piezocapacitive pressure sensors, and reviews their progress. To secure high sensitivity in piezoresistive and piezocapacitive pressure sensors, materials and structures that generate a large amount of deformation for the same pressure are essential [19,20]. If a material with a low modulus of elasticity is utilized, a larger deformation can be obtained for the same pressure. There are technologies that use three-dimensional (3D) porous structures to generate a deformation greater than that obtained through material change [21]. In addition, there are key methods for improving sensitivity by maximizing the change in the contact area or distance between electrodes at the same pressure, using 3D protrusion structures. A 3D sensor is a sensor that forms a

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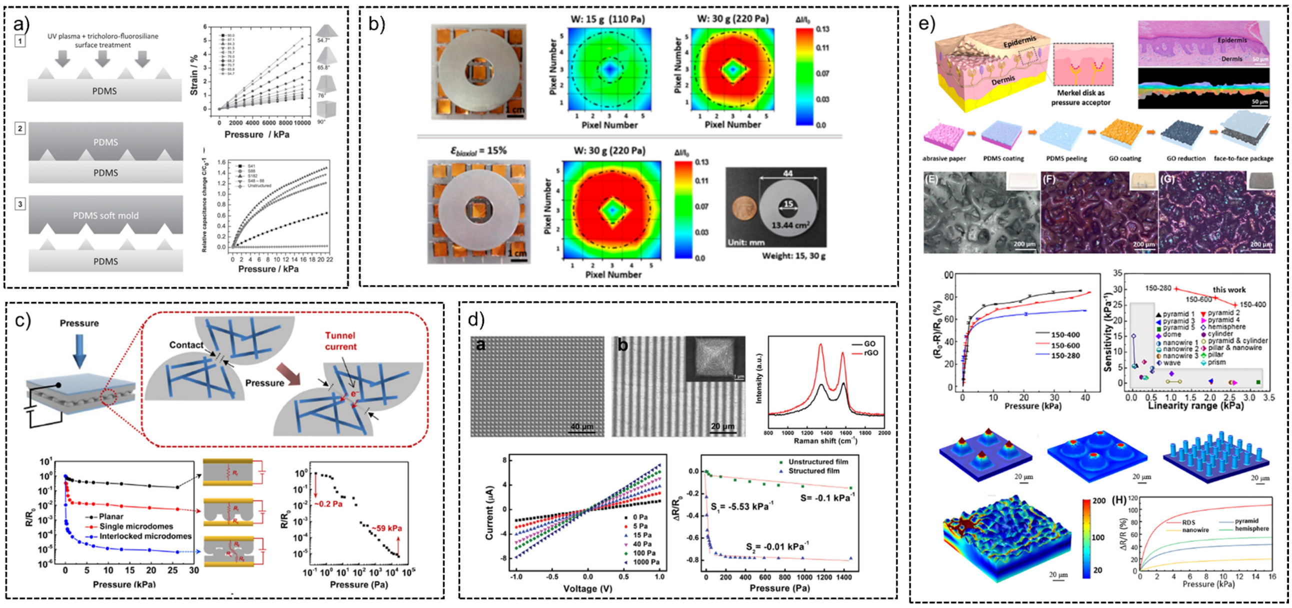

Fig. 1. 3D microstructure pressure sensors. (a) Flexible pressure sensor using microstructured elastomer though the silicon molding and demolding process. Reprinted with permission from Ref. [22]. Copyright (2019) John Wiley and Sons. (b) Stretchable sensitive pressure sensor consisting of nanofibers and micropillars. Reprinted with permission from Ref. [23]. Copyright (2015) American Chemical Society. (c) Tunneling piezoresistance of composite elastomers with microdome structures. Reprinted with permission from Ref. [24]. Copyright (2014) American Chemical Society. (d) Microstructured graphene arrays for highly sensitive flexible tactile sensors. Reprinted with permission from Ref. [25]. Copyright (2014) John Wiley and Sons. (e) Graphene pressure sensor with random distributed spinosum. Reprinted with permission from Ref. [26]. Copyright (2018) American Chemical Society

structure having length, breadth and height inside or outside.

In this paper, the ongoing efforts for increasing the sensitivity of pressure sensors, and the progress of various studies on materials, structures, and manufacturing methods, are reviewed. In addition, some high-sensitivity flexible pressure sensor applications are introduced. Finally, the limitations of flexible pressure sensor studies, and their development directions are discussed.

2. FLEXIBLE PRESSURE SENSORS WITH 3D STRUCTURE

Constructing microstructures such as pyramids, domes, and pillars is an effective approach for fabricating flexible pressure sensors with high sensitivity. Microstructures on the surface of a sensor's active layer reduces elastic resistance owing to the air void in the film, resulting in excellent sensing performance. A flexible pressure sensor based on Polydimethylsiloxane (PDMS) dielectric layers formed into microstructured pyramids is shown in Fig. 1a. The microstructured PDMS dielectric layer was produced by a prefabricated patterned mold using lithography and etching. The microstructured dielectric layer not only improves the sensitivity by over 27 times compared to unstructured PDMS dielectric layers, but also decreases the relaxation time because of reduced viscoelastic property of the PDMS dielectric layer [22]. Fig. 1b. shows an ultra-sensitive sensor using micropillars and nanofibers, and at the same time shows a stretchable sensor with no change in pressure recognition even with a 15 % change in biaxial stress. The sensor's pressure recognition resolution is 15 Pa and the response time is very short, at 50 ms [23]. In addition, piezoresistive flexible pressure sensors based on microstructures have been suggested. Fig. 1c shows an interlocked microdome array with high-sensitivity achieved due to giant tunneling piezoresistance. The external pressure induces stress concentration at the tips of the microdomes, resulting in large local deformations. They demonstrated high sensitivity as 15.1 kPa^{-1} in the low-pressure range (under 0.5 kPa) and excellent sensing performance such as fast response time, limit of detection, and high reliability [24]. Zhu et al., also suggested piezoresistive flexible pressure sensors based on microstructured graphene arrays to improve sensor sensitivity, as shown in Fig. 1d. They verified that the flexible pressure sensor exhibited a high sensitivity of −5.53 kPa^{-1} for a pressure range of 100 Pa, excellent limit of detection capability of 1.5 Pa [25]. Pang et al., proposed randomly distributed microstructures for highly sensitive pressure sensor through the combination of an abrasive paper template and

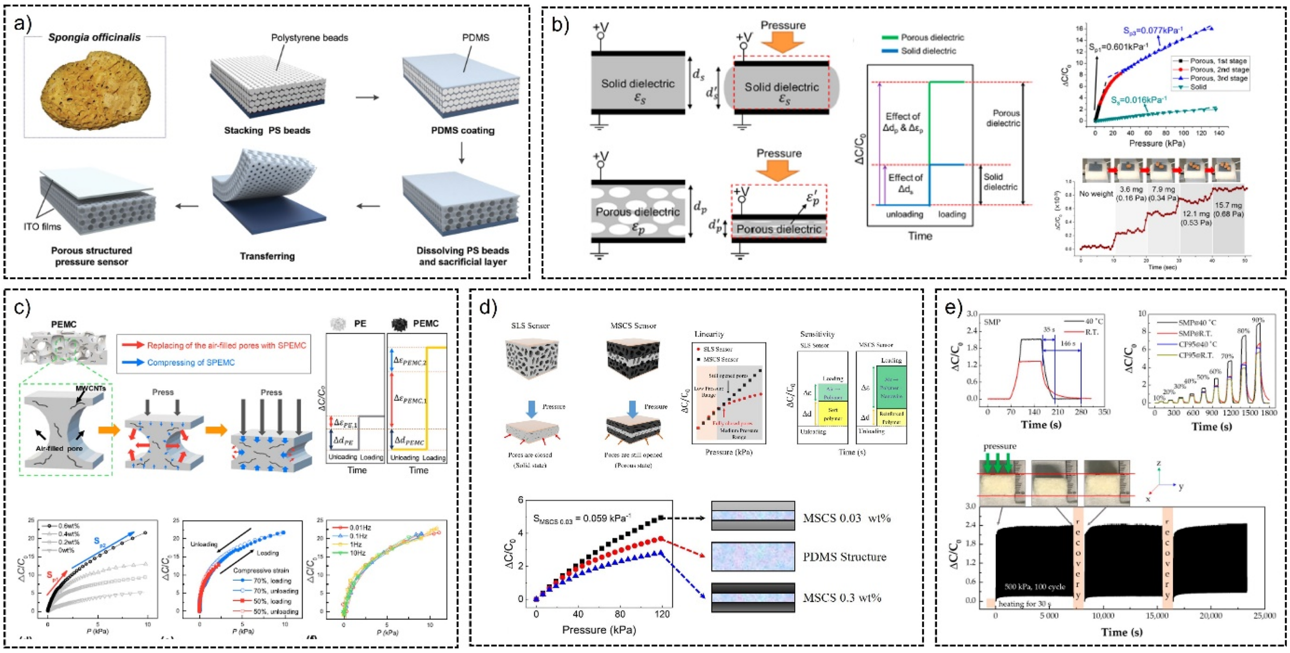

Fig. 2. 3D porous structural pressure sensors. (a) Flexible pressure sensor based on bioinspired porous structure. Reprinted with permission from Ref. [27]. Copyright (2016) John Wiley and Sons. (b) Flexible pressure sensor based on 3D microporous elastomeric dielectric layer using sugar templating process. Reprinted with permission from Ref. [28]. Copyright (2016) American Chemical Society. (c) Capacitive pressure sensor based on porous elastomer and percolation of carbon nanotube filler. Reprinted with permission from Ref. [29]. Copyright (2020) American Chemical Society. (d) Multistacked composite porous structural pressure sensor for improving linearity. Reprinted with permission from Ref. [30]. Copyright (2021) American Chemical Society. (e) Shape-memory polymer-based flexible sensor that recovers its shape by itself depending on the temperature. Reprinted with permission from Ref. [31]. Copyright (2021) Multidisciplinary Digital Publishing Institute.

reduced graphene oxide, as shown in Fig. 1e. They verified pressure distribution for pressure sensors with different surface geometries using simulation. Polymeric 3D porous structures are typically employed as a dielectric layer in flexible pressure sensor to detect wide pressure ranges. The polymeric porous structures are easily compressed even at small pressures owing to reduced elastic resistance and the anti-barreling phenomenon [26]. Kang et al., suggested bioinspired porous structure for highly sensitive pressure sensor via stacking polystyrene (PS) beads, PDMS coating, and dissolving PS beads as shown in Fig. 2a [27]. The porous structured pressure sensor exhibited a high sensitivity of 0.63 kPa^{-1}, an excellent limit of detection of 2.42 Pa, and stability over 10000 working cycles. Fig. 2b shows a flexible pressure sensor based on the giant piezocapacitive effect of 3D porous dielectric layer. The combination of large deformation and an increased dielectric constant of the 3D porous dielectric layer under applied pressure significantly improve the overall sensor performance. Through this structure, they demonstrated that pressure sensor exhibited high sensitivity of 0.601 kPa^{-1} in a wide pressure range (0.1 Pa to 130 kPa), which is appropriate for applying to various practical applications [28]. Several studies have been proposed to increase sensing performance, such as sensitivity, linearity, and durability, in conjunction with the development of a 3D porous structure-based pressure sensor. Fig. 2c illustrates the flexible pressure sensor based on a 3D porous composite structure mixed with Ecoflex matrix and carbon nanotubes (CNT), which leads to an improvement in sensor sensitivity due to the synergetic effect of the percolation of CNT fillers [29]. Fig. 2d shows the fabrication of a pressure sensor composed of stacked CNT and PDMS layer. With the addition of CNT in the porous structure, the porous structure is linearly compressed with applied pressure due to the reinforced mechanical properties, thereby resulting in linear sensitivity over a wide pressure range [30]. Finally, Park et al., also suggested shape memory polymer-based pressure sensors with notable durability at a high-pressure range. Shape memory polymers have the capability to return from a deformed state to their original state when induced by applied heat. The fabricated shape memory polymer-based pressure sensor exhibited similar signal values after 100 cycles of applied pressure at 500 kPa and were applied to human motion detection application on a shoe insole [31]. In recent years, flexible pressure sensors based on 3D structure have

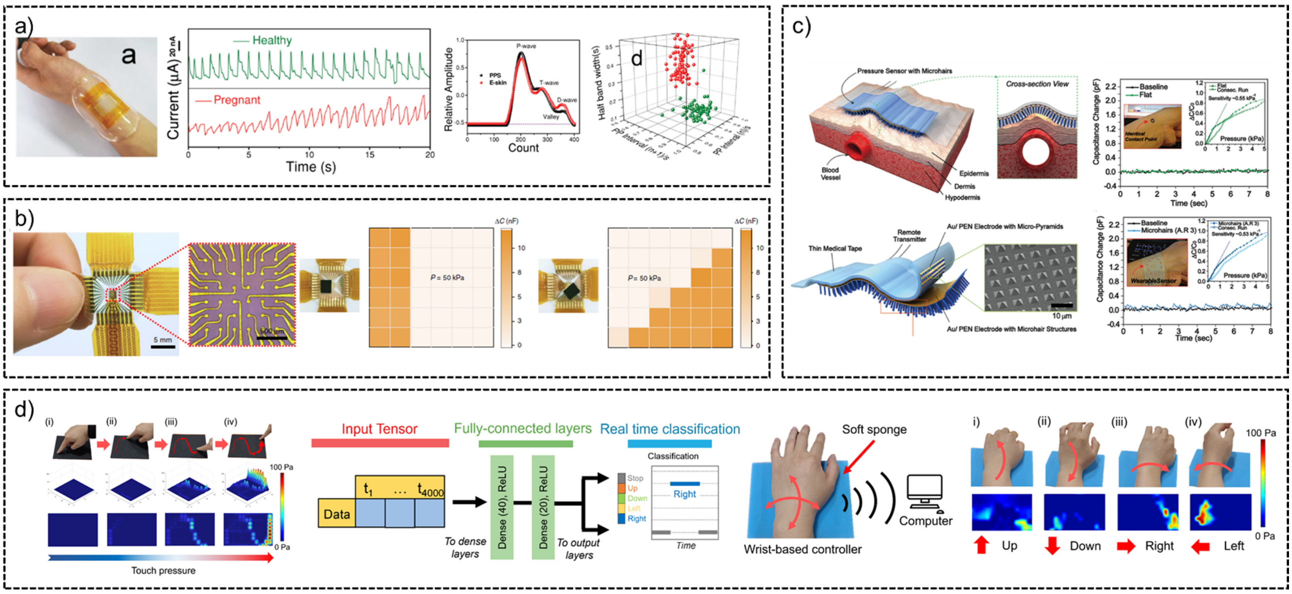

Fig. 3. Applications of the flexible pressure sensors based on 3D structure. Health monitoring, pattern recognition, motion detection, and human-computer interaction. (a)Electronic skin for monitoring human physiological signal. Reprinted with permission from Ref. [32]. Copyright (2014) John Wiley and Sons. (b) Iontronic pressure sensor array for monitoring ultra-wide range sensitivity. Reprinted with permission from Ref. [33]. Copyright (2020) Springer Nature. (c) Highly skin-conformal micro-hair sensor for pulse signal amplification. Reprinted with permission from Ref. [34]. Copyright (2014) John Wiley and Sons. (d) Irregular Microdome Structure-Based Sensitive Pressure Sensor for human-machine interface. Reprinted with permission from Ref. [35]. Copyright (2022) John Wiley and Sons.

made significant developments and have been applied in various fields. Fig. 3a shows a flexible pressure sensor for monitoring the radial wrist artery in people with different physical conditions. The typical pulse characteristics were collected and segregated into the following categories. The Percussion wave (P-wave), Tidal wave (T-wave), and Diastolic wave (D-wave), which are related to clinical information [32]. A sensor array based on a 3D structure of 6 × 6 pixels was developed, as shown in Fig. 3b. The sensor array fully detected and recorded location and pressure information of the objects [33]. Using the bio-inspired micro-hair structure, the research group has developed an ultra-sensitive capacitive sensor that simultaneously increases sensitivity and reduces hysteresis, as shown in Fig. 3c [34]. It was confirmed that this was sufficient for monitoring patients with cardiac abnormalities, and for identifying differences caused by the presence or absence of disease. Finally, a pressure sensor with high sensitivity was applied to a large-area sensor array pad for human-computer interaction, as shown in Fig. 3d [35]. The fabricated sensor array pad was applied to the drawing application, and the gradually increased pressure level was recorded, according to the curved trajectory. The sensor array pad based on a flexible pressure sensor clearly distinguished different patterns caused by different wrist movements and demonstrated the control of the mouse cursor.

3. CONCLUSIONS

Owing to their three-dimensional structure, flexible pressure sensors can sense pressure better than conventional pressure sensors. Currently, they are applied to various fields such as healthcare, gesture recognition, and human-machine interface. To develop a more sensitive and linear sensor, research on various 3D structures is continuously being conducted. In addition, manufacturing methods for 3D structures are being studied. The protruding 3D structure increases the sensitivity of the sensor through local deformation and ensures repeatability through material selection. A 3D porous structure increases sensor sensitivity on account of its low elastic modulus caused by internal pores, which increase the amount of deformation for the same force. Researchers continue to push the boundary on flexible pressure sensors that have high sensitivity, excellent linearity, and good productivity. Efforts are also being made to expand the field of application of the developed flexible pressure sensors.

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REFERENCES

[1] X. Wang, L. Dong, H. Zhang, R. Yu, C. Pan, and Z. L. Wang, "Recent Progress in Electronic Skin", *Adv. Sci.* (Weinh), Vol. 2, No. 10, pp. 1500169(1)-1500169(22), 2015.

[2] A. Chortos, J. Liu, and Z. Bao, "Pursuing prosthetic electronic skin", *Nat. Mater.*, Vol. 15, No. 9, pp. 937-950, 2016.

[3] K. Kim, J. Choi, Y. Jeong, I. Cho, M. Kim, S. Kim, Y. Oh, and I. Park, "Highly Sensitive and Wearable Liquid Metal-Based Pressure Sensor for Health Monitoring Applications: Integration of a 3D-Printed Microbump Array with the Microchannel", *Adv. Healthc. Mater.*, Vol. 8, No. 22, pp. e1900978(1)-e1900978(10), 2019.

[4] W. Honda, S. Harada, T. Arie, S. Akita, and K. Takei, "Wearable, Human-Interactive, Health-Monitoring, Wireless Devices Fabricated by Macroscale Printing Techniques", *Adv. Funct. Mater.*, Vol. 24, No. 22, pp. 3299-3304, 2014.

[5] T. Gong, H. Zhang, W. Huang, L. Mao, Y. Ke, M. Gao, and B. Yu, "Highly responsive flexible strain sensor using polystyrene nanoparticle doped reduced graphene oxide for human health monitoring", *Carbon*, Vol. 140, pp. 286-295, 2018.

[6] H. H. Lee, J. H. Choi, J. I. Ahn, C. S. Kim, and J. K. Shin, "A Simple Capacitive Sensor Array Based on a Metal-Insulator-Metal Structure", *J. Sens. Sci. Technol.,* Vol. 21, No. 2, pp. 83-89, 2012.

[7] Y. E. Kwon, Y. Y. Kim, Y. G. Lee, D. K. Lee, O. W. Kwon, S. W. Kang, and K. H. Lee, "Body Pressure Distribution and Textile Surface Deformation Measurement for Quantification of Automotive Seat Design Attributes", *J. Sens. Sci. Technol.*, Vol. 27, No. 6, pp. 397-402, 2018.

[8] Y. Zang, F. Zhang, C.-a. Di, and D. Zhu, "Advances of flexible pressure sensors toward artificial intelligence and health care applications", *Mater. Horiz.*, Vol. 2, No. 2, pp. 140-156, 2015.

[9] J. Ge, L. Sun, F. R. Zhang, Y. Zhang, L. A. Shi, H. Y. Zhao, H. W. Zhu, H. L. Jiang, and S. H. Yu, "A Stretchable Electronic Fabric Artificial Skin with Pressure-, Lateral Strain-, and Flexion-Sensitive Properties", *Adv. Mater.*, Vol. 28, No. 4, pp. 722-728, 2016.

[10] Z. Ma, W. Wang, and D. Yu, "Highly Sensitive and Flexible Pressure Sensor Prepared by Simple Printing Used for Micro Motion Detection", *Adv. Mater. Interfaces*, Vol. 7, No. 2, pp. 1901704(1)-1901704(7), 2019.

[11] O. Atalay, A. Atalay, J. Gafford, and C. Walsh, "A Highly Sensitive Capacitive-Based Soft Pressure Sensor Based on a Conductive Fabric and a Microporous Dielectric Layer", *Adv. Mater. Tech.*, Vol. 3, No. 1, pp. 1700237(1)-1700237(8), 2017.

[12] S. J. Woo, J. H. Kong, D. G. Kim, and J. M. Kim, "A thin all-elastomeric capacitive pressure sensor array based on micro-contact printed elastic conductors", *J. Mater. Chem. C*, Vol. 2, No. 22, pp. 4415-4422, 2014.

[13] H. Li, Y. Zhang, H. Dai, W. Tong, Y. Zhou, J. Zhao, and Q. An, "A self-powered porous ZnS/PVDF-HFP mechanoluminescent composite film that converts human movement into eye-readable light", *Nanoscale*, Vol. 10, No. 12, pp. 5489-5495, 2018.

[14] Q. Gao, H. Meguro, S. Okamoto, and M. Kimura, "Flexible tactile sensor using the reversible deformation of poly(3-hexylthiophene) nanofiber assemblies", *Langmuir*, Vol. 28, No. 51, pp. 17593-17596, 2012.

[15] M. Wang, N. Zhang, Y. Tang, H. Zhang, C. Ning, L. Tian, W. Li, J. Zhang, Y. Mao, and E. Liang, "Single-electrode triboelectric nanogenerators based on sponge-like porous PTFE thin films for mechanical energy harvesting and self-powered electronics", *J. Mater. Chem. A Mater.* , Vol. 5, No. 24, pp. 12252-12257, 2017.

[16] D. H. Kwon, J. H. Kwon, J. Jeong, Y. Lee, S. Biswas, D. W. Lee, S. Lee, J. H. Bae and H. Kim, "Textile Triboelectric Nanogenerators with Diverse 3D-Spacer Fabrics for Improved Output Voltage", *Electronics*, Vol. 10, No. 8, 2021.

[17] J. H. Kwon, J. Jeong, Y. Lee, S. Biswas, J. K. Park, S. Lee, D. W. Lee, S. Lee, J. H. Bae and H. Kim, "Importance of Architectural Asymmetry for Improved Triboelectric Nanogenerators with 3D Spacer Fabrics", *Macromol. Res.*, Vol. 29, No. 6, pp. 443-447, 2021.

[18] D. K. Kim, J. B. Jeong, K. Lim, J. Ko, P. Lang, M. Choi, S. Lee, J. H. Bae and H. Kim, "Improved Output Voltage of a Nanogenerator with 3D Fabric", *J. Nanosci. Nanotechnol.*, Vol. 20, No. 8, pp. 4666-4670, 2020.

[19] S. C. Mannsfeld, B. C. Tee, R. M. Stoltenberg, C. V. Chen, S. Barman, B. V. Muir, A. N. Sokolov, C. Reese, and Z. Bao, "Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers", *Nat. Mater.*, Vol. 9, No. 10, pp. 859-864, 2010.

[20] B. C. K. Tee, A. Chortos, R. R. Dunn, G. Schwartz, E. Eason, and Z. Bao, "Tunable Flexible Pressure Sensors using Microstructured Elastomer Geometries for Intuitive Electronics", *Adv. Funct. Mater.*, Vol. 24, No. 34, pp. 5427-5434, 2014.

[21] S. Chen, B. Zhuo, and X. Guo, "Large Area One-Step Facile Processing of Microstructured Elastomeric Dielectric Film for High Sensitivity and Durable Sensing over Wide Pressure Range", *ACS Appl. Mater. Interfaces,* Vol. 8, No. 31, pp. 20364-20370, 2016.

[22] B. C. K. Tee, A. Chortos, R. R. Dunn, G. Schwartz, E. Eason, and Z. Bao, "Tunable Flexible Pressure Sensors using Microstructured Elastomer Geometries for Intuitive Electronics", *Adv. Funct. Mater.,* Vol. 24, No. 34, pp. 5427-5434, 2014.

[23] H. Park, Y. R. Jeong, J. Yun, S. Y. Hong, S. Jin, S. J. Lee, G. Zi, and J. S. Ha, "Stretchable Array of Highly Sensitive Pressure Sensors Consisting of Polyaniline Nanofibers and Au-Coated Polydimethylsiloxane Micropillars", *Acs Nano.*, Vol. 9, No. 10, pp. 9974-9985, 2015.

[24] J. Park, Y. Lee, J. Hong, M. Ha, Y. D. Jung, H. Lim, S. Y. Kim, and H. Ko, "Giant Tunneling Piezoresistance of Composite Elastomers with Interlocked Microdome Arrays for

Ultrasensitive and Multimodal Electronic Skins", *Acs Nano*., Vol. 8, No. 5, pp. 4689-4697, 2014.

[25] B. Zhu, Z. Niu, H. Wang, W. R. Leow, H. Wang, Y. Li, L. Zheng, J. Wei, F. Huo, and X. Chen, "Microstructured graphene arrays for highly sensitive flexible tactile sensors", *Small*, Vol. 10, No. 18, pp. 3625-3631, 2014.

[26] Y. Pang, K. Zhang, Z. Yang, S. Jiang, Z. Ju, Y. Li, X. Wang, D. Wang, M. Jian, Y. Zhang, R. Liang, H. Tian, Y. Yang, and T. L. Ren, "Epidermis Microstructure Inspired Graphene Pressure Sensor with Random Distributed Spinosum for High Sensitivity and Large Linearity", *ACS Nano*, Vol. 12, No. 3, pp. 2346-2354, 2018.

[27] S. Kang, J. Lee, S. Lee, S. Kim, J.-K. Kim, H. Algadi, S. Al-Sayari, D.-E. Kim, D. Kim and T. Lee, "Highly Sensitive Pressure Sensor Based on Bioinspired Porous Structure for Real-Time Tactile Sensing", *Adv. Electr. Mater.*, Vol. 2, No. 12, 2016.

[28] D. Kwon, T. I. Lee, J. Shim, S. Ryu, M. S. Kim, S. Kim, T. S. Kim, and I. Park, "Highly Sensitive, Flexible, and Wearable Pressure Sensor Based on a Giant Piezocapacitive Effect of Three-Dimensional Microporous Elastomeric Dielectric Layer", *ACS Appl. Mater. Interfaces*, Vol. 8, No. 26, pp. 16922-16931, 2016.

[29] J. Choi, D. Kwon, K. Kim, J. Park, D. D. Orbe, J. Gu, J. Ahn, I. Cho, Y. Jeong, Y. Oh, and I. Park, "Synergetic Effect of Porous Elastomer and Percolation of Carbon Nanotube Filler toward High Performance Capacitive Pressure Sensors", *ACS Appl. Mater. Interfaces*, Vol. 12, No. 1, pp. 1698-1706, 2020.

[30] Y. Jung, T. Lee, J. Oh, B. G. Park, J. S. Ko, H. Kim, J. P. Yun and H. Cho, "Linearly Sensitive Pressure Sensor Based on a Porous Multistacked Composite Structure with Controlled Mechanical and Electrical Properties", *ACS Appl. Mater. Interfaces*, Vol. 13, No. 24, pp. 28975-28984, 2021.

[31] B. Park, Y. Jung, J. S. Ko, J. Park and H. Cho, "Self-Restoring Capacitive Pressure Sensor Based on Three-Dimensional Porous Structure and Shape Memory Polymer", *Polym.* (Basel), Vol. 13, No. 5, pp. 824(1)-824(9), 2021.

[32] X. Wang, Y. Gu, Z. Xiong, Z. Cui, and T. Zhang, "Silk-molded flexible, ultrasensitive, and highly stable electronic skin for monitoring human physiological signals", *Adv. Mater.*, Vol. 26, No. 9, pp. 1336-1342, 2014.

[33] N. Bai, L. Wang, Q. Wang, J. Deng, Y. Wang, P. Lu, J. Huang, G. Li, Y. Zhang, J. Yang, K. Xie, X. Zhao, and C. F. Guo, "Graded intrafillable architecture-based iontronic pressure sensor with ultra-broad-range high sensitivity", *Nat. Commun.,* Vol. 11, No. 1, pp. 209(1)-209(9), 2020.

[34] C. Pang, J. H. Koo, A. Nguyen, J. M. Caves, M. G. Kim, A. Chortos, K. Kim, P. J. Wang, J. B. Tok and Z. Bao, "Highly skin-conformal microhairy sensor for pulse signal amplification", *Adv. Mater.*, Vol. 27, No. 4, pp. 634-640, 2015.

[35] Y. Jung, J. Choi, W. Lee, J. S. Ko, I. Park and H. Cho, "Irregular Microdome Structure-Based Sensitive Pressure Sensor Using Internal Popping of Microspheres", *Adv. Funct. Mater.*, pp. 2201147(1)-2201147(12), 2022.