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Triboelectrification based Multifunctional Tactile Sensors

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Abstract

Advanced tactile sensors are receiving significant attention in various industries such as extended reality, electronic skin, organic user interfaces, and robotics. The capabilities of advanced tactile sensors require a variety of functions, including position sensing, pressure sensing, and material recognition. Moreover, they should comsume less power and be bio-friendly with human contact. Recently, a tactile sensor based on the triboelectrification effect was developed. Triboelectric tactile sensors have the advantages of wide material availability, simple structure, and low manufacturing cost. Because they generate electricity by contact, they have low power consumption compared to conventional tactile sensors such as capacitive and piezoresistive. Furthermore, they have the ability to recognize the contact material as well as execute position and pressure sensing functions using the triboelectrification effect. The aim of this study is to introduce the progress of research on triboelectrification-based tactile sensors with various functions such as position sensing, pressure sensing and contact material recognition.

Keywords: Tactile sensors, Triboelectrification, Position sensors, Pressure sensors, Contact material recognition

1. INTRODUCTION

The global COVID-19 pandemic has driven our lives into non-face-to-face situations. It has transformed us into digital in various fields such as online meetings, digital classes, online concerts, and remote conferences. Consequently, we are entering the metaverse era, a collaborative virtual shared space created by combining virtually enhanced physical reality and physically enduring virtual spaces. Although augmented reality and virtual reality technologies have received significant attention, they have not grosewn as expected because of the lack of content and devices. The development of various advanced functional devices is required to realize a hyperconnected and hyperrealistic digital world. A multifunctional tactile sensor is an essential device for realizing telehaptic technology that exchanges tactile experiences, and is one of the core technologies of metaverse. The development of advanced tactile sensors is also required for various future applications, such as robots, electronic skin, and organic user interfaces. Future tactile sensors should operate with low power consumption and have multiple functionalities, including position sensing, pressure sensing, and material recognition. Technologies currently used for tactile sensors include capacitive [1-4], piezocapacitive [5,6], resistive [7], piezoresistive [8-10], piezoelectric and triboelectric type [11-13]. Touch sensors, such as capacitive and resistive sensors, are limited in terms of recognizing pressure. Piezoresistive and piezocapacitive pressure sensors can sense the contact position and pressure; they require a continuous power supply, which results in high power consumption. In addition, all the aforementioned sensors do not recognize the texture or type of contact material, except the triboelectric type, which is a key function for future tactile sensor applications. A triboelectric-type tactile sensor can recognize the contact material, because the generated voltage varies depending on the contact material.

The operation mechanism of the triboelectric tactile sensor is coupling effect of triboelectrification and electrostatic induction, as shown in Fig. 1 [14]. The triboelectrification effect occurs when two different substances contact each other, and electrostatic induction is due to a change in the electric field caused by the movement of the two charged materials. A triboelectric tactile sensor generates electricity through contact, and the generated voltage is related to the triboelectric properties of the materials [15,16]. Therefore, a triboelectric tactile sensor can recognize the contact material. Owing to the wide selection of materials for the triboelectric layer, a light, inexpensive, and transparent material

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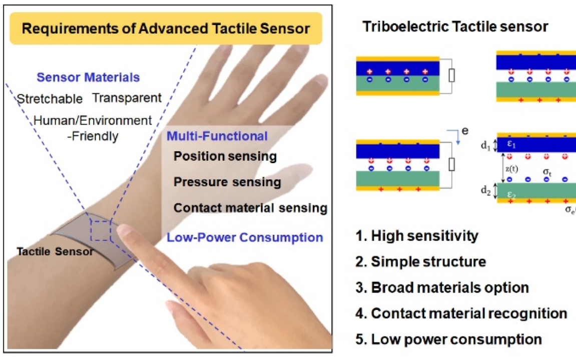

Fig. 1. Advanced Triboelectric Tactile Sensor

can be used for triboelectric tactile sensors, which are suitable for electronic skin and wearable applications and can be easily miniaturized and commercialized.

Herein the research progress of triboelectric tactile sensors is reviewed with a discussion on the development and future of tactile sensor technology.

This review summarizes the various types of triboelectric tactile sensors for real-time monitoring and virtual reality applications with position sensing [11,17-22], pressure sensing [23-28], and material recognition [5,12,29-32] functions. We discuss the structural development and sensing mechanisms of the device.

2. MULTIFUNCTIONAL TACTILE SENSORS

Position detection functions is the most basic function for determing the contact position in the tactile sensor. Fig. 2. shows position sensors that detect the contact location through triboelectrification. Pu, X. et al. reported the 3D triboelectric touchpad (3D TTP) with an X and Y comprehensive subdivision pattern (XYCSP) in Fig. 2(a) [17]. XYCSP consists of a diagonal connection of subdivided squares, consisting of electrode layers of the row electrode layer, column electrode layer, and tribo-layer (fluorinated ethylene propylene). It senses the position by measuring the output of each electrode that occurs when it comes into contact. It can be a flexible position sensor based on a flexible substrate. Shi, Q. et al. reported a triboelectric patch consisting of four divided ring-shaped electrode layers and a tribo-layer (polytetrafluoroethylene) as given in Fig. 2(b) [18]. They can detect not only eight regions but also drag inside and outside the

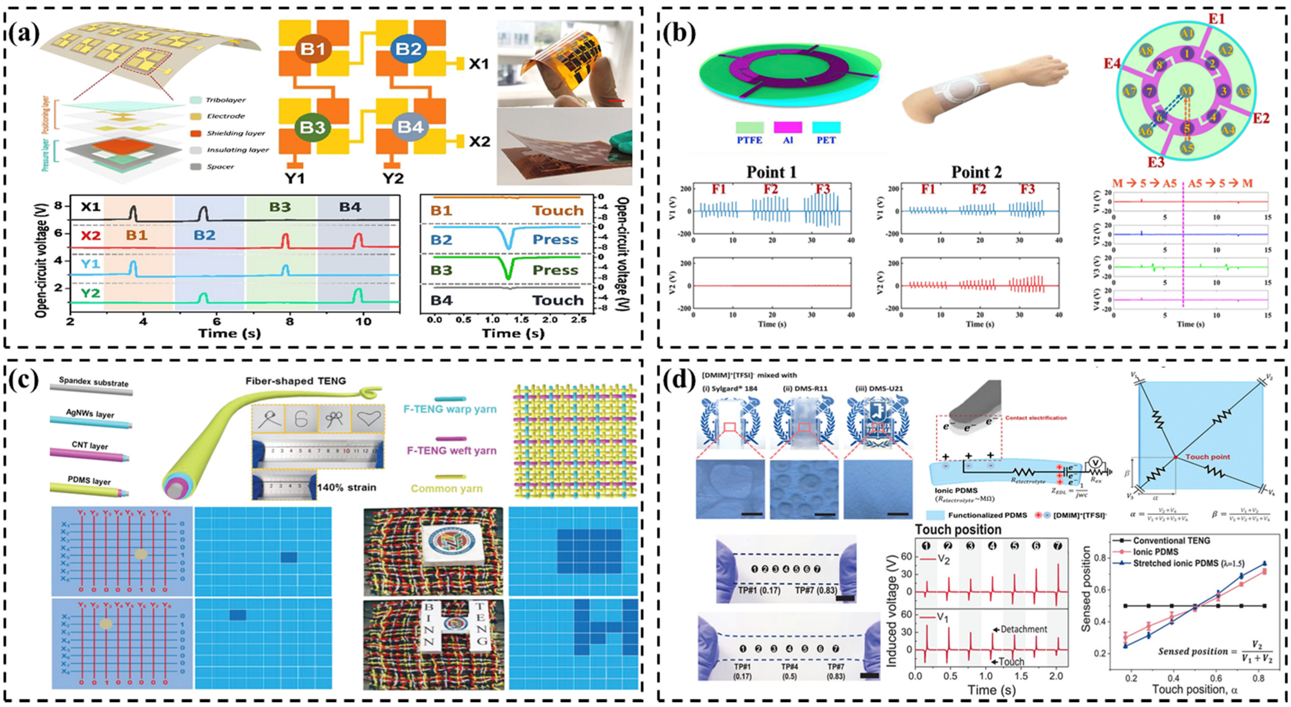

Fig. 2. Triboelectric position sensors. (a) Flexible triboelectric 3D touchpad with unit subdivision structure for effective XY positioning and pressure sensing. Reprinted with permission from Ref. [17]. Copyright (2020) Elsevier. (b) Minimalist and multi-functional human-machine interface (HMI) using a flexible wearable triboelectric patch. Reprinted with permission from Ref. [18]. Copyright (2019) Elsevier. (c) Flexible and stretchable fiber-shaped triboelectric nanogenerators for biomechanical monitoring and human-interactive sensing. Reprinted with permission from Ref. [19]. Copyright (2020) John Wiley and Sons. (d) Triboresistive touch sensing: grid-free touch-point recognition based on monolayered ionic power generators. Reprinted with permission from Ref. [20]. Copyright (2022) John Wiley and Sons.

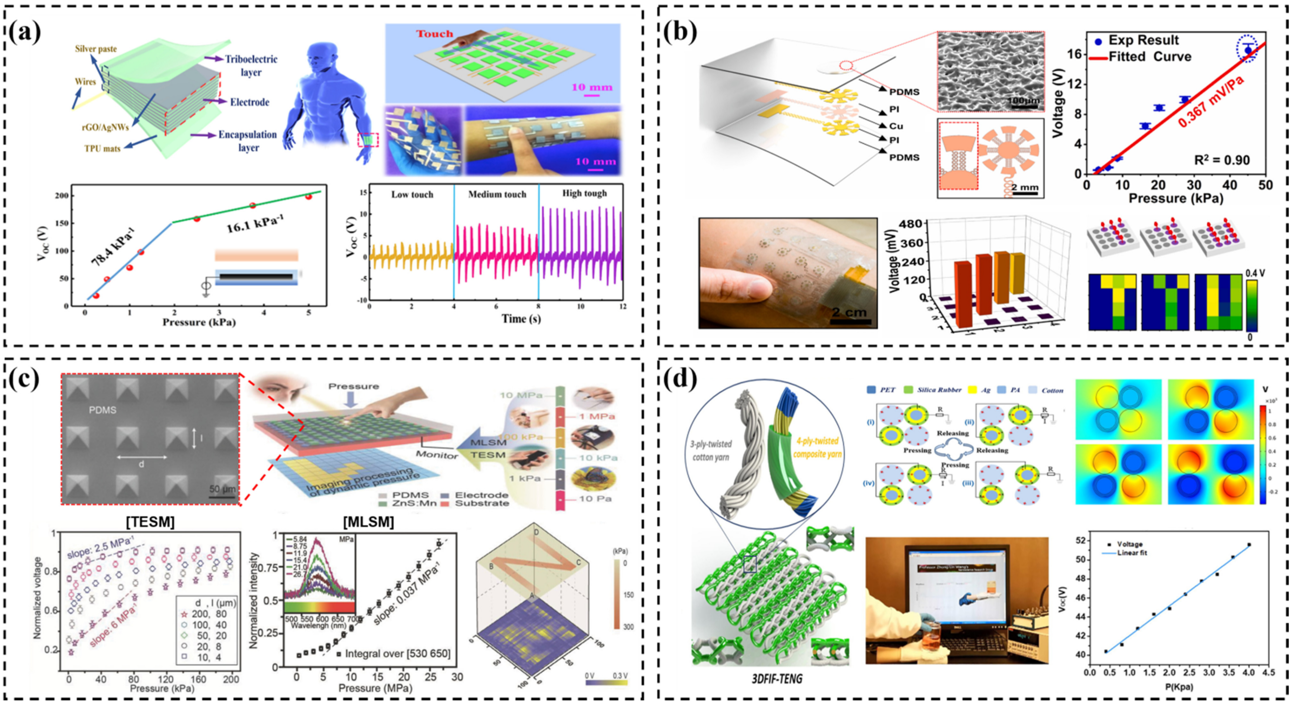

Fig. 3. Triboelectric pressure sensors. (a) Ultra-stretchable triboelectric nanogenerator as high-sensitive and self-powered electronic skins for energy harvesting and tactile sensing. Reprinted with permission from Ref. [23]. Copyright (2020) Elsevier. (b) Trampoline inspired stretchable triboelectric nanogenerators as tactile sensors for epidermal electronics. Reprinted with permission from Ref. [24]. Copyright (2021) Elsevier. (c) Full dynamic-range pressure sensor matrix based on optical and electrical dual-mode sensing. Reprinted with permission from Ref. [25]. Copyright (2017) John Wiley and Sons. (d) 3D double-faced interlock fabric triboelectric nanogenerator for biomotion energy harvesting and as self-powered from stretching and 3D tactile sensors. Reprinted with permission from Ref. [26]. Copyright (2020) Elsevier.

electrodes by utilizing individual and common junction areas of the four electrodes. Triboelectric patch wearable applications can be developed based on these functions. Ning, C et al. reported a textile form of triboelectric position sensor as composite fiber and spandex fiber of Spandex/Ag nanowire/carbon nanotube/ Polydimethylsiloxane(PDMS) in Fig. 2(c) [19]. Since the conductive fibers are arranged on the x-axis and y-axis, the corresponding x and y generate output to detect the touching position. Because it is a textile form using stretchable fiber, it is applied to wearable applications suitable for contact-release and bend-stretch mode. Lee, Y. et al. reported a tribo-resistive position sensor with an ionic PDMS monolayer in Fig. 2(d) [20]. Unlike the previous three papers [12-15], there is no electrode grid for position sensing. The conductive ionic PDMS can sense the position using the tribo-resistive characteristics, in which the output decreases as the distance contacted increases. The accuracy of the position sensor can be increased by utilizeing the four electrodes on the edges of the ionic PDMS.

The pressure sensing function is also one of the most basic functions to detect a physical quantity applied to the tactile sensor. Fig. 3. shows triboelectrification pressure sensors. The measuring principle of the triboelectric pressure sensor is that when the force applied to the contact material increases, the deformation of the material increases, resulting in more friction surface charge. Zhou, K. et al. reported an ultra-stretchable triboelectric pressure consisting of a multilayer structure of ultra-layered thermoplastic polyurethane/Ag nanowires/reduced graphene oxide in Fig. 3(a) [23]. The pressure sensitivity is 78.4 kPa-1 in the 0-2 kPa area and 16.1 kPa-1 in the 2-5 kPa area, which is excellent at low pressure. In addition, it has a fast response rate (1.4 ms), hence it is suitable for real-time monitoring. He, J. et al. reported a trampoline-type triboelectric pressure sensor based on the structural mechanism design in Fig. 3(b) [24]. The pressure sensitivity was 0.367 mV/ Pa over a wide pressure range (0 to 50 kPa). In addition, the 2D trampoline sensing array triboelectric tactile sensor can be applied to various types of curved surfaces owing to its excellent stretchability. Wang, X. et al. reported a hybrid pressure sensor consisting of a triboelectric sensor matrix (TESM) and a mechanoluminescent sensor matrix (MLSM) in Fig. 3(c) [25]. This structure can detect wide range of pressure because the TESM has a high sensitivity (6 MPa-1) in the low-pressure area (<100 kPa), and the MLSM has a high sensitivity (0.037 MPa-1)

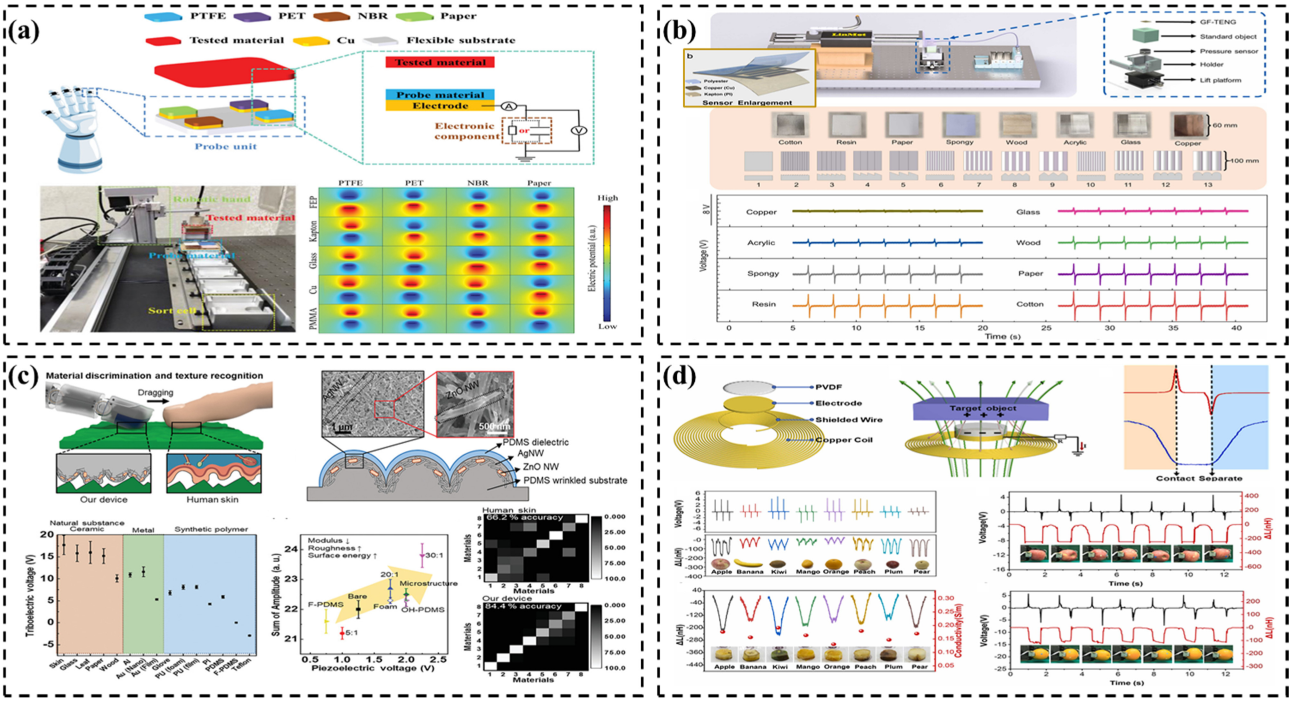

Fig. 4. Triboelectric contact material recognition sensors. (a) A flexible triboelectric tactile sensor for simultaneous material and texture recognition. Reprinted with permission from Ref. [29]. Copyright (2022) Elsevier. (b) Material Recognition Sensor Array by Electrostatic Induction and Triboelectric Effects. Reprinted with permission from Ref. [30]. Copyright (2020) John Wiley and Sons. (c) Fingerpad-Inspired Multimodal Electronic Skin for Material Discrimination and Texture Recognition. Reprinted with permission from Ref. [31]. Copyright (2021) John Wiley and Sons. (d) A triboelectric-inductive hybrid tactile sensor for highly accurate object recognition. Reprinted with permission from Ref. [5]. Copyright (2020) Elsevier.

in the high-pressure area (>1 MPa). Chen, C. et al. reported the 3D double-faced interlock fabric (3DFIF) triboelectric tactile sensor using cotton yarn and conductive composite yarn shown in Fig. 3(d) [26]. 3DFIF triboelectric tactile sensor produces excellent output in contact-separation and bend-stretch mode and can be used as a pressure sensor and bending sensor.

Future tactile sensors will need the ability to recognize contact materials and textures just like real human skin. Fig. 4. shows the material recognition sensor. Song, Z. et al. reported a material sensor array consisting of a probe unit made of flexible materials in Fig. 4(a) [29]. The probe unit comprises four materials (paper, polytetrafluoroethylene, poly ethylene terephthalate, nitrile-butadiene rubber). When contacted with tested materials, the object can be distinguished using electric potential outputs and signals according to triboelectric properties. However, there is a disadvantage that accuracy is low because the output difference is insignificant. Several variables affect the triboelectric potential, such as the film thickness, active area of the contact, and dielectric properties. Rong, X. et al. reported a grating-structural free-standing triboelectrification-based material sensing system in Fig. 4(b) [30]. It is a system that detects the material and its texture simultaneously based on a deep learning model using signals generated when a grating-structural free-standing tactile sensor and an object with macro/micro structure come into contact. It can distinguish eight types of objects such as cotton, resin, paper, and 13 types of surface textures, and the accuracy is as high as 98% or more. There is a limitation that material and pressure are not recognized simultaneously because of the limitation of the grating-structural free-standing tactile sensor mechanism. Lee, G. et al. reported a finger pad-inspired electronic skin-based material recognition sensor shown in Fig. 4(c) [31]. The human hand recognition mechanism can recognize the shear force produced when dragging through three stages: mechanical stimulation, pressure, tensile deformation, and vibration. Similarly, the wrinkled PDMS/Ag nanowire-based triboelectric and piezoelectric hybrid sensor can detect the texture of an object by analyzing the piezoelectric output signal according to pressure using the friction charge output signal. Li, N. et al. reported a hybrid tactile sensor integrating a triboelectric active sensing unit with an electronic induction transducer shown in Fig. 4(d) [5]. The triboelectric layer consisting of polyvinylidene fluoride (PVDF) and copper electrodes produces a surface charge interaction when contacting the target. An inductance sensor consisting of copper coils measures the target's electromagnetic induction. Triboelectric and inductance hybrid sensors can identify objects by comprehensively analyzing output signals according to fruit type, shape, size, conductivity, and moisture content.

3. CONCLUSIONS

The future tactile sensor is required to operate in an irregular shape rather than a flat shape, so the degree of freedom of the sensor in shape must be high. It is also necessary to have low-power consumption, multi-functionalities, transparent, human/environmentally friendly, stretchable, and attachable to the skin to increase user convenience. Triboelectric tactile sensors detect position, pressure, and contact material. Since a triboelectric tactile sensor can be implemented without a complex electrode grid pattern, it is easy to lower the process cost and realize a sensor with a complex shape. In addition, the triboelectric sensor has the advantage of low power consumption because power is generated by contact/pressure motion. It can be employed as a real-time monitoring sensor in applications such as health monitoring, smart gloves for extended reality, and robot control. This review discuss flexible triboelectric tactile sensors that detect position and pressure for applications in attachable touchpads, wearable textiles, and electronic skins. In addition, a material recognition system was developed using triboelectric properties and machine-learning technology. Apart from recognizing various contact materials, the texture of the material can be recognized by mimicking the material recognition mechanism of a human finger. Moreover, the hybrid-type sensor with the induction sensor could determine the shape, size, electrical conductivity, and moisture content of the fruit. Nevertheless, there are still various limitations to the commercialization of triboelectric tactile sensors. First, the accuracy and sensitivity of the sensor are still low compared with thoese of conventional tactile sensors. Second, the types of objects that can recognize materials are limited. Until now, materials used for triboelectric tactile sensors have been limited. Along with the development of novel materials exhibiting high sensitivity, flexibility, and transparency, it is necessary to develop manufacturing technology that can reduce production costs and simplify processes to be suitable for commercial and practical use.

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REFERENCES

[1] D. P. Cotton, I. M. Graz, and S. P. Lacour, "A multifunctional capacitive sensor for stretchable electronic skins", *IEEE Sens. J.,* Vol. 9, No. 12, pp. 2008-2009, 2009.
[2] D. S. Kang, M. J. Kim, and W. K. Moon, "Optimization of a capacitive sensor for high dynamic range", *J. Sens. Sci. Technol.,* Vol. 19, No. 2, pp. 92-98, 2010.
[3] W. Kim, H. Lee, K.-N. Lee, and K. Kim, "A Polymer-based Capacitive Air Flow Sensor with a Readout IC and a Temperature Sensor", *J. Sens. Sci. Technol.,* Vol. 28, No. 1, pp. 1-6, 2019.
[4] S. Xu, Y. Zhang, L. Jia, K. E. Mathewson, K. I. Jang, J. Kim, H. Fu, X. Huang, P. Chava, and R. Wang, "Soft microfluidic assemblies of sensors, circuits, and radios for the skin", *Sci.,* Vol. 344, No. 6179, pp. 70-74, 2014.
[5] N. Li, Z. Yin, W. Zhang, C. Xing, T. Peng, B. Meng, J. Yang, and Z. Peng, "A triboelectric-inductive hybrid tactile sensor for highly accurate object recognition", *Nano Energy.,* Vol. 96, p. 107063, 2022.
[6] 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.
[7] F. Reverter, J. Jordana, M. Gasulla, and R. Pallàs-Areny, "Accuracy and resolution of direct resistive sensor-to-microcontroller interfaces", *Sens. Actuators A Phy.,* Vol. 121, No. 1, pp. 78-87, 2005.
[8] T. Sandner, H. Conrad, T. Klose, and H. Schenk, "Integrated piezo-resistive positionssensor for microscanning mirrors", in *2007 IEEE/LEOS Int. Conf. Opt. MEMS Nanophotonics*, 2007: IEEE, pp. 195-196, 2007.
[9] W. J. Kim, Y. S. Cho, H. J. Kang, and S. Y. Choi, "Development of miniature weight sensor using piezoresistive pressure sensor", *J. Sens. Sci. Technol.,* Vol. 14, No. 4, pp. 237-243, 2005.
[10] H. J. Bae, S. H. Son, and S. Y. Choi, "Fabrication of silicon piezoresistive pressure sensor for a biomedical in-vivo measurements", *J. Sens. Sci. Technol.,* Vol. 10, No. 3, pp. 148-155, 2001.
[11] X. Wang, Y. Zhang, X. Zhang, Z. Huo, X. Li, M. Que, Z. Peng, H. Wang, and C. Pan, "A highly stretchable transparent self-powered triboelectric tactile sensor with metallized nanofibers for wearable electronics", *Adv. Mater.,* Vol. 30, No. 12, p. 1706738, 2018.
[12] C. M. Boutry, M. Negre, M. Jorda, O. Vardoulis, A. Chortos, O. Khatib, and Z. Bao, "A hierarchically patterned, bioinspired e-skin able to detect the direction of applied pressure for robotics", *Sci. Robot.,* Vol. 3, No. 24, p. eaau6914, 2018.
[13] J. Wang, P. Cui, J. Zhang, Y. Ge, X. Liu, N. Xuan, G. Gu, G. Cheng, and Z. Du, "A stretchable self-powered triboelectric tactile sensor with EGaIn alloy electrode for ultra-low-pressure detection", *Nano Energy.,* Vol. 89, p. 106320, 2021.

[14] Z. L. Wang, L. Lin, J. Chen, S. Niu, and Y. Zi, "Triboelectric nanogenerator: Vertical contact-separation mode", *in Triboelectric Nanogenerators*: Springer, pp. 23-47, 2016.
[15] H. Zou, Y. Zhang, L. Guo, P. Wang, X. He, G. Dai, H. Zheng, C. Chen, A. C. Wang, and C. Xu, "Quantifying the triboelectric series", *Nat. Commun.,* Vol. 10, No. 1, pp. 1-9, 2019.
[16] H. J. Ryoo, C. W. Lee, J. W. Han, W. Kim, and D. Choi, "A Triboelectric Nanogenerator Design for the Utilization of Multi-Axial Mechanical Energies in Human Motions", *J. Sens. Sci. Technol.,* Vol. 29, No. 5, pp. 312-322, 2020.
[17] X. Pu, Q. Tang, W. Chen, Z. Huang, G. Liu, Q. Zeng, J. Chen, H. Guo, L. Xin, and C. Hu, "Flexible triboelectric 3D touch pad with unit subdivision structure for effective XY positioning and pressure sensing", *Nano Energy.,* Vol. 76, p. 105047, 2020.
[18] Q. Shi, Z. Zhang, T. Chen, and C. Lee, "Minimalist and multi-functional human machine interface (HMI) using a flexible wearable triboelectric patch", *Nano Energy.,* Vol. 62, pp. 355-366, 2019.
[19] C. Ning, K. Dong, R. Cheng, J. Yi, C. Ye, X. Peng, F. Sheng, Y. Jiang, and Z. L. Wang, "Flexible and stretchable fiber-shaped triboelectric nanogenerators for biomechanical monitoring and human-interactive sensing", *Adv. Funct. Mater.,* Vol. 31, No. 4, p. 2006679, 2021.
[20] Y. Lee, S. Lim, W. J. Song, S. Lee, S. J. Yoon, J. M. Park, M. G. Lee, Y. L. Park, and J. Y. Sun, "Triboresistive Touch Sensing: grid-free Touch Point Recognition Based on Monolayered Ionic Power Generators", *Adv. Mater.,* p. 2108586, 2022.
[21] T. Chen, Q. Shi, M. Zhu, T. He, L. Sun, L. Yang, and C. Lee, "Triboelectric self-powered wearable flexible patch as 3D motion control interface for robotic manipulator", *ACS nano.,* Vol. 12, No. 11, pp. 11561-11571, 2018.
[22] T. Chen, Q. Shi, K. Li, Z. Yang, H. Liu, L. Sun, J. A. Dziuban, and C. Lee, "Investigation of position sensing and energy harvesting of a flexible triboelectric touch pad", *Nanomaterials.,* Vol. 8, No. 8, p. 613, 2018.
[23] K. Zhou, Y. Zhao, X. Sun, Z. Yuan, G. Zheng, K. Dai, L. Mi, C. Pan, C. Liu, and C. Shen, "Ultra-stretchable triboelectric nanogenerator as high-sensitive and self-powered electronic skins for energy harvesting and tactile sensing", *Nano Energy.,* Vol. 70, p. 104546, 2020.
[24] J. He, Z. Xie, K. Yao, D. Li, Y. Liu, Z. Gao, W. Lu, L. Chang, and X. Yu, "Trampoline inspired stretchable triboelectric nanogenerators as tactile sensors for epidermal electronics", *Nano Energy.,* Vol. 81, p. 105590, 2021.
[25] X. Wang, M. Que, M. Chen, X. Han, X. Li, C. Pan, and Z. L. Wang, "Full dynamic-range pressure sensor matrix based on optical and electrical dual-mode sensing", *Adv. Mater.,* Vol. 29, No. 15, p. 1605817, 2017.
[26] C. Chen, L. Chen, Z. Wu, H. Guo, W. Yu, Z. Du, and Z. L. Wang, "3D double-faced interlock fabric triboelectric nanogenerator for bio-motion energy harvesting and as self-powered stretching and 3D tactile sensors", *Materials Today,* Vol. 32, pp. 84-93, 2020.
[27] Y. W. Cai, X. N. Zhang, G. G. Wang, G. Z. Li, D. Q. Zhao, N. Sun, F. Li, H. Y. Zhang, J. C. Han, and Y. Yang, "A flexible ultra-sensitive triboelectric tactile sensor of wrinkled PDMS/MXene composite films for E-skin," *Nano Energy.,* Vol. 81, p. 105663, 2021.
[28] B. Ji, Q. Zhou, B. Hu, J. Zhong, J. Zhou, and B. Zhou, "Bio-Inspired Hybrid Dielectric for Capacitive and Triboelectric Tactile Sensors with High Sensitivity and Ultrawide Linearity Range," *Adv. Mater.,* Vol. 33, No. 27, p. 2100859, 2021.
[29] X. Rong, J. Zhao, H. Guo, G. Zhen, J. Yu, C. Zhang, and G. Dong, "Material recognition sensor array by electrostatic induction and triboelectric effects," *Advanced Materials Technologies,* Vol. 5, No. 9, p. 2000641, 2020.
[30] Z. Song, J. Yin, Z. Wang, C. Lu, Z. Yang, Z. Zhao, Z. Lin, J. Wang, C. Wu, and J. Cheng, "A flexible triboelectric tactile sensor for simultaneous material and texture recognition", *Nano Energy.,* Vol. 93, p. 106798, 2022.
[31] G. Lee, J. H. Son, S. Lee, S. W. Kim, D. Kim, N. N. Nguyen, S. G. Lee, and K. Cho, "Fingerpad-Inspired Multimodal Electronic Skin for Material Discrimination and Texture Recognition", *Adv. Sci.,* Vol. 8, No. 9, p. 2002606, 2021.
[32] X. Zhao, Z. Zhang, L. Xu, F. Gao, B. Zhao, T. Ouyang, Z. Kang, Q. Liao, and Y. Zhang, "Fingerprint-inspired electronic skin based on triboelectric nanogenerator for fine texture recognition", *Nano Energy.,* Vol. 85, p. 106001, 2021.